BIOMECHANICS OF MOVEMENT-RELATED EFFORT: EFFECTS OF TASK

By

Bryan M. Bond

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Thesis Committee:

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Chairperson, Phillip Gallagher, Ph.D.

____
Andrew Fry, Ph.D.

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Phillip Vardiman, Ph.D.

____
Robert Gregory, Ph.D.

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The Thesis Committee for Bryan Bond certifies that this is the approved version of the following thesis:

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Chairperson, Phillip Gallagher, Ph.D.

Date approved: _____________________

ABSTRACT

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Key Words: Effort, Task, Biomechanics, Unimanual, Bimanual

Based upon the importance of effort in determining human movement, it is essential to develop a thorough understanding of the biomechanical quantities generated during specified movements. **PURPOSE:** To examine how movement-related effort changes between unilateral and bilateral movements involving the elbow joint. **METHODS:** Ten healthy, young (20-40 years of age), right-hand dominant males participated in the study. Subjects performed repeated elbow flexion/extension movements in the horizontal plane during unilateral (dominant and non-dominant arms) and bilateral (in-phase and anti-phase) tasks at a frequency of 2.0 Hz. Subjects produced angular displacements that corresponded to effort levels of 1, 3, 5, 7, and 9 on a modified Borg-CR10 scale. Motion capture measured the angular position of the elbow joint. Mean angular displacement (MAD), peak angular velocity (PAV), peak angular acceleration (PAA), and peak joint torque (PJT) were calculated for each condition. A three-way ANOVA assessed the effects of arm, task and effort on MAD, PAV, PAA and PJT. **RESULTS:** There was a significant main effect of task on MAD ($F_{2,8} = 40.04$, $P < 0.0001$), PAV ($F_{2,8} = 27.54$, $P < 0.0001$), PAA ($F_{2,8} = 15.22$, $P < 0.0001$), and PJT ($F_{2,8} = 14.04$, $P < 0.0005$). In addition, there was a significant main effect of effort level on MAD ($F_{4,6} = 103.70$, $P < 0.0001$), PAV ($F_{4,6} = 89.32$, $P < 0.0001$), PAA ($F_{4,6} = 56.34$, $P < 0.0001$), and PJT ($F_{4,6} = 60.94$, $P < 0.0001$). There was also a significant main effect of arm on MAD ($F_{1,9} = 6.72$, $P < 0.05$), PAV ($F_{1,9} = 7.41$, $P < 0.05$), and PAA ($F_{1,9} = 8.21$, $P < 0.05$). However, the main effect of arm on PJT was not significant ($F_{1,9} = 1.44$, $P = 0.26$). **CONCLUSION:** This study demonstrated the influence of task on movement-related effort through quantification of biomechanical measures. During unilateral tasks, there is an increased sense of effort when using the non-dominant arm due to strength and motor coordination differences. During bilateral tasks, there is a decreased sense of effort when performing in-phase movements due to increased pattern stability.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Fundamental questions in biomechanics and motor control research are how and why certain movements are performed, while others that could be executed are not. Is one movement chosen over another because of physical or environmental constraints? Researchers in the motor control discipline have struggled with the predicament of the excessive degrees of freedom associated with human movement. For a prescribed task, there are an infinite number of movement choices available. The infinite degrees of freedom dilemma associated with human movement is named the Bernstein problem (Turvey, 1990). Plausible theories for explaining the control of human movements include the inverse dynamics approach, generalized motor program theory, equilibrium point hypothesis, and optimal control approach.

The inverse dynamics approach reports that the central nervous system (CNS) plans a movement using kinematic parameters as inputs to a biomechanical model (Dounskaia, 2010). The resulting output from the model consists of a set of joint torques that produces the planned movement. The generalized motor program theory suggests that the brains acts like a computer, storing previous movements in memory, and retrieving and executing motor programs according to the required movement demands. According to the equilibrium point hypothesis, the muscles within the body behave like springs with the resting length controlled by the CNS. As two antagonistic muscle groups change length, an imbalance of elastic energy results in joint movement, followed by transition to a new equilibrium point so that the two muscle forces equate again. The optimal control approach postulates that the CNS determines the optimal cost associated with the required movement, such as muscle energy expenditure or movement time. The CNS then relays the optimized neural command to the appropriate muscles. Although helpful in explaining human movement, each of the four theories described above have significant limitations.

Another possible reason for a chosen movement is related to the effort required to perform the task. Since the late 1950's, researchers have investigated the psychological concept of perceived effort. Ratings of perceived effort are often used in the fields of physiology, psychology, exercise science, ergonomics, and medicine. A few specific applications include exercise stress tests for cardiovascular disease, occupational lifting techniques, and exercise pacing during athletic training/racing (Borg, 1990; Noble, 1982).

In the field of biomechanics, research has focused on the reduction of effort in the performance of movement. Andrews (1983) suggested that several kinematic and kinetic parameters may be associated with effort, but this claim was not validated. However, further research validated Andrews' assertions regarding effort and human movement. Previous researchers found a positive relationship between effort ratings and torque values (Burgess, Cooper, Gottlieb, & Latash, 1995). Rosenbaum and Gregory (2002) reported acceptable intra-class correlation coefficients for angular displacement, peak angular velocity, and peak angular acceleration associated with specified effort levels. These authors also demonstrated an acceptable validity coefficient between net joint torque and effort level across specified movement frequencies.

Based on current research, it appears that movement choices are not entirely governed by physical limitations or interactions among limb segments. Rather, for normal individuals, a significant factor in determining the movement performed is the level of effort associated with task; the effort level of the performed movement is often lower. Since activities of daily living frequently involve unilateral and bilateral movements, it is important to assess effort levels associated with these everyday tasks.

Based upon the importance of effort in determining human movement, it is essential to develop a thorough understanding of the biomechanical quantities generated during unilateral and bilateral movements. Previous research has explored effort while performing specific, complex tasks, but these studies have not reported on effort related to upper extremity unilateral or bilateral tasks (Borg, 1990; Noble, 1982; Robertson et al., 2004). Thus, to further understand the complexities of human movement, the effects of task and effort on kinematic and kinetic measures needs to be investigated.

1.1 Problem Statement

The current study quantified the effects of task on movement-related effort during dynamic elbow joint movements using biomechanical parameters. The subjects performed elbow flexion and extension movements at five effort levels (1, 3, 5, 7, and 9 on a modified Borg CR-10 scale) according to four movement tasks: unilateral dominant, unilateral non-dominant, bilateral in-phase, and bilateral anti-phase. The specific aim of this research project was:

(1) To examine how movement-related effort changes between unilateral and bilateral movements involving the elbow joint.

1.2 Independent Variables

The independent variables in this experiment were:

(1) The effort level performed during the elbow joint movement. The subjects performed voluntary contraction of their elbow joint flexors and extensors at

specified effort level ratings of 1, 3, 5, 7, or 9, according to a modified Borg CR-10 scale, such that 0 = “no effort” and 10 = “maximal effort”.

(2) The task performed with the elbow joint movement. The subjects performed voluntary contraction of their elbow joint flexors and extensors during four conditions: unilateral dominant, unilateral non-dominant, bilateral in-phase, and bilateral anti-phase.

(3) The elbow joint used while performing the specified movement. The subjects performed voluntary contraction of their elbow joint flexors and extensors using their dominant and/or non-dominant limbs.

1.3 Dependent Variables

The dependent variables for this experiment were:

(1) The angular displacement (°) associated with the elbow joint motion.

(2) The peak angular velocity (°/s) associated with the elbow joint motion.

(3) The peak angular acceleration ($°/s^2$) associated with the elbow joint motion.

(4) The peak torque (N·m) associated with the elbow joint motion.

The constant variable for this experiment was:

(1) The elbow joint motion frequency at 2 Hertz (Hz).

1.4 Hypotheses

It is hypothesized that:

(1) Angular displacement will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

a. Angular displacement will be greater for the dominant limb than non-dominant limb.

b. Angular displacement will be greater for the unilateral than bilateral tasks.

c. Angular displacement will be greater for the in-phase than anti-phase tasks.

(2) Peak angular velocity will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

a. Peak angular velocity will be greater for the dominant limb than non-dominant limb.

b. Peak angular velocity will be greater for the unilateral than bilateral tasks.

c. Peak angular velocity will be greater for the in-phase than anti-phase tasks.

(3) Peak angular acceleration will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

a. Peak angular acceleration will be greater for the dominant limb than non-dominant limb.

b. Peak angular acceleration will be greater for the unilateral than bilateral tasks.

c. Peak angular acceleration will be greater for the in-phase than anti-phase tasks.

(4) Peak joint torque will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase).

   a. Peak joint torque will be greater for the dominant limb than non-dominant limb.

   b. Peak joint torque will be greater for the unilateral than bilateral tasks.

   c. Peak joint torque will be greater for the in-phase than anti-phase tasks.

1.5 Definitions

Angular acceleration: change in angular velocity during a specified time interval.

Angular displacement: change in angular position as the limb moves through a range of motion.

Angular velocity: change in angular displacement during a specified time interval.

Anti-phase: asynchronous upper limb movements that are out of sequence by 180 degrees.

Bilateral: having or relating to two sides of the body.

Dominant: preferred limb to perform fine and gross motor tasks.

Effort: a psychological construct corresponding to an individual's sense of difficulty in achieving a task in a specific way.

Elbow joint: formed by the humero-ulnar and humero-radial joints allowing flexion and extension.

In-phase: synchronized upper limb movements.

Non-dominant: non-preferred limb to perform fine and gross motor tasks.

Peak torque: single highest torque (rotational torsion about an axis) produced by muscular contraction as the limb moves through a range of motion.

Unilateral: having or relating to only one side of the body.

1.6 Assumptions and Limitations

(1) Ten healthy males 20-40 years old participated in the study. The sample may not represent the larger population.

(2) A single-joint task involving the elbow was analyzed. This joint may not represent other limbs or joints.

(3) A single, fixed movement frequency of 2 Hz. This does not represent the only frequency at which the human body is capable of moving.

1.7 Significance

This was the first research investigation to compare the biomechanics of movement-related effort between unilateral and bilateral tasks. Specifically, this study determined changes in effort associated with hand dominancy during unilateral, dynamic dominant and non-dominant elbow joint movements. Also, this experiment directly compared the sense of effort between bilateral, dynamic synchronized (in-phase) and non-synchronized (anti-phase) elbow joint movements.

It was important to investigate the effects of tasks on the relationship between movement-related effort and biomechanical parameters in order to determine changes in human performance. In order to better comprehend physical performance and work capacity, there was a significant demand for effort ratings in normal, clinical, and special populations (Borg, 1990; Noble, 1982; Robertson & Noble, 1997). For example, with a predictable linear relationship between joint torque and effort during unilateral and bilateral movements, the slope of the line may be used during rehabilitation to assess whether or not a patient improved with corrective exercise.

CHAPTER 2

REVIEW OF LITERATURE

To better understand why one movement is chosen over another, a discussion of topics related to human motion and effort are necessary. Relevant topics include a definition of effort along with quantification scales, motor control influences and biomechanical parameters associated with effort.

2.1 Perceived Effort

Since the late 1950's, researchers in human movement sciences have often investigated the psychological concept of perceived effort; however, the challenge of quantifying perceived effort remains. A number of terms have been used in the scientific literature to describe this psychological concept including perceived exertion, perceived effort, and sense of effort. Perceived exertion is defined as the "subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise" (Robertson & Noble, 1997). The single best indicator of physical strain is perceived effort (Borg, 1982). Perceived exertion results from the integration of information from the peripheral working muscles and joints, the central cardiovascular and respiratory functions, and the central nervous system; all these signals, perceptions, and experiences are termed a 'Gestalt' of perceived exertion (Borg, 1982). Rosenbaum et al. (1996) described effort as a psychological construct corresponding to an individual's sense of difficulty in achieving a task in a specific way.

Ratings of perceived effort are often used in the fields of physiology, psychology, exercise science, ergonomics, and medicine. A few specific applications include exercise stress tests for cardiovascular disease, occupational lifting techniques, and exercise pacing during athletic training/racing (Noble, 1982). In order to better comprehend physical performance and work capacity/limitations, effort ratings in normal, clinical, and special populations are needed.

2.2 Measurement of Effort

In order to quantitatively measure a person's perception of effort during physical activity, researchers use a scale for rating effort. Category scales have been developed in an attempt to measure perceived effort (Borg, 1982, 1990). These include a 21-point, graded scale with values ranging from 0 (no exertion at all) to 20 (maximum exertion); a 15-point, graded scale named the Borg rating perceived exertion (RPE) scale with values ranging from 6 (no exertion at all) to 20 (maximum exertion); and an 11-point, graded scale entitled the CR-10 scale with values ranging from 0 (nothing at all) to 10 (extremely strong).

Experimental research failed to correlate the 21-point scale with heart rate in a linear relationship (Borg, 1982). However, both the Borg RPE and the CR-10 scales demonstrated a strong correlation between heart rate and perceived exertion during exercise (Borg, 1982). Additional perceived effort scales are the OMNI picture system (Robertson et al., 2000; Robertson et al., 2004; Robertson et al., 2003) and modified Borg CR-10 scales (Pincivero, Coelho, & Erikson, 2000; Pincivero, Gandaio, & Ito, 2003).

2.2.1 Reliability and Validity of Effort Scales

Perceived exertion or effort scales have been validated (O'Sullivan, 1984) by correlating effort with corresponding oxygen consumption, pulmonary ventilation, respiratory rate, or joint torque. Validity correlations for these scales range from $r = 0.56$ to 0.94, while the reliability coefficients range from $r = 0.78$ to 0.95 (Mihevic, 1981;

Robertson, 1982). More recently, in a population of adolescent girls performing treadmill exercise, intra-class and single-trial reliability estimates were higher for the OMNI (r_{xx} = 0.95 and r_{kk} = 0.91, respectively) compared with the Borg (r_{xx} = 0.78 and r_{kk} = 0.64, respectively) RPE scale (Pfeiffer, Pivarnik, Womack, Reeves, & Malina, 2002). Also, validity coefficients (r_{xy}) for $\%HR_{max}$ and $\%VO_{2max}$ were 0.86 and 0.89, respectively, for the OMNI, and 0.66 and 0.70, respectively, for the Borg. A meta-analysis of the validity of the Borg ratings of perceived exertion scales revealed the weighted mean validity coefficients were 0.62 for heart rate, 0.57 for blood lactate, 0.64 for $\%VO_{2max}$, 0.63 for VO_2, 0.61 for ventilation, and 0.72 for respiration rate (Chen, Fan, & Moe, 2002). These validity and reliability coefficients for numerical rating scales are acceptable measures for determining the physiological, psychological, and biomechanical mediators of effort.

2.3 Motor Control of Muscular Effort

2.3.1 Physiological Measures of Perceived Effort

The quantitative analysis of perceived effort is confounded by physiological variables and psychological factors. It is challenging to correlate perceived effort with physiological and psychological variables, either by extrapolation or direct measurement. Dominant cues for perceived effort include central systemic factors such as heart rate and minute ventilation, and local factors such as blood lactate and muscle discomfort (Russell, 1997). It appears that local factors dominate perceived effort at low to moderate exercise intensities, while central factors dominate at high exercise intensity (Russell, 1997).

Local factors that may provide sensory input for perceived exertion include muscle lactate, Golgi tendon activity, and general muscle sensations (Mihevic, 1981).

Previous research implies that lactate concentration may serve as a sensory cue for the perception of effort, although at relatively low exercise intensities (Mihevic, 1981). The elevated perception of effort associated with exercise suggests that sensory input from the exercising limbs is a critical perceptual cue for evaluating exertion during exercise (Mihevic, 1981).

Central factors affecting perceived effort include heart rate, oxygen consumption (VO_2), ventilatory minute volume (V_E), and respiration rate (RR) (Mihevic, 1981). Although there is a strong linear relationship between heart rate and perceived exertion across many exercise intensities, the independence of heart rate and perceptual responses with pharmacological and environmental manipulations suggests that perceived exertion is not only influenced by heart rate. The perception of effort is related to relative metabolic demands during exercise, but there is minimal evidence that the individual monitors oxygen consumption during exercise. According to Mihevic (1981), ventilation and respiration rate may be consciously monitored during exercise providing another source of sensory information for the perception of effort during movement.

2.3.2 Psychological Measures of Perceived Effort

Studies examining perceived effort and psychological traits have demonstrated that while normal subjects can detect differences in load, those subjects who are neurotic, anxious, or depressed have difficulty in perceiving work intensity (Russell, 1997). The more anxious and neurotic the person, the lower the perceptual rating (Morgan, 1994). Also, extroversion is inversely correlated with perceived exertion, and positively correlated with preferred exercise intensity (Morgan, 1994). Psychological interventions such as hypnotic suggestion, dissociative cognitive strategies, and imagery may increase or decrease perception of effort in a systemic manner (Morgan, 1994).

2.3.3 Kinaesthesia

The phenomena of kinesthesia include the sensations of proprioception, the sensations of force, effort, and heaviness of muscular contractions, and the sensations of perceived timing of muscular contractions (Gandevia, McCloskey, & Burke, 1992). Muscle spindles play a major role in generating the sensation of passive movement. While comparing active versus passive movements, the discharge of muscle spindles increases during voluntary isometric contraction. When a movement is applied to a subject during a voluntary muscular contraction, there is an enhanced ability to detect the direction of applied movement. Detection of the threshold for passive movement is ten times greater than it is for active movement (Gandevia et al., 1992).

Innervation of the skin is divided into two receptor types: rapid and slow adapting. The rapidly adapting receptors include Meissner’s (RA receptors) and Pacinian corpuscles (PC receptors), while the slowly adapting receptors include Merkel cell neurite complexes (SA I receptors) and Ruffini endings (SA II receptors) (Gandevia et al., 1992). These receptors have been studied to examine their perceptual effects. With anesthesia of the skin and joint afferents, the ability to discern passive movements is not lost (Gandevia et al., 1992).

One motor control theory suggests that signals are produced from within the CNS, or together with the commands for muscular contractions (McCloskey, Gandevia, Potter, & Colebatch, 1983). These signals influence sensory perception either by changing the processing of afferent information or by entering higher cortical areas to produce, in their own right, sensations of various types. The size of the centrally generated voluntary motor commands influences movement decisions rather than the sensations related to actual tensions and pressures reached within the muscles (McCloskey et al., 1983).

Previous research has examined the role of the sensory system in mediating movement (Jones, 1986, 1994, 1995). Jones (1994) suggests that the term proprioception has three components including the perceptions of position, movement (both amplitude and angular velocity), and force. Muscle spindles and cutaneous mechanoreceptors mediate the perception of limb position. Muscle spindles, cutaneous mechanoreceptors, and joint receptors provide information to the nervous system about limb movement. Golgi tendon organs and neural correlates that arise from the descending motor command provide information about the perception of muscle force.

Jones (1995) proposed that the perception of effort is primarily derived from either a central origin or a peripheral pathway. Central sensations involve information arriving from the innervation of the efferent pathways, while the peripheral sensations emanate from the muscles, skin, and joints (Jones, 1994). Centrally mediated sensations are described as sense of effort, while the peripheral sensory information is called sense of force or tension. Golgi tendon organs are the most likely source of information about the sense of force. Sensations of effort and force should be considered complimentary, since both are involved with the perception of force (Jones, 1995).

Anytime a change in the voluntary generated motor command produces a muscle contraction, there is a parallel change in the perceived amplitude of the force produced by the muscle (Jones, 1995). However, evidence does not directly support a proportional relationship between the central and peripheral systems.

With muscle fatigue, the sense of effort influences the perception of muscle force (Jones, 1995). During fatiguing activities, it is challenging for subjects to estimate the actual forces produced by muscle. Research involving muscle paresis also suggests a centrally mediated perception of force. With paresis, there is an increase in the efferent signal needed to generate a specified level of muscle force (Jones, 1995). Yet, the peripheral afferent discharges from muscle spindle and tendon organs continue to signal the actual force of contraction. However, limitations within this area of research include designing an experiment in which tendon organs are the only source of force information (Jones, 1995).

The review of literature provided four relevant conclusions about kinaesthesia (Gandevia et al., 1992). First, a coherent discharge of cutaneous, muscle, or joint mechanoreceptors cannot be completely ignored by the CNS when calculating limb proprioception. Second, all afferent receptors can carry specific aspects of movement and can elicit perception of movement. Third, movement appears to enhance kinaesthetic acuity, and fourth, muscle contraction improves proprioceptive acuity.

2.4 Biomechanics of Muscular Effort

2.4.1 Biomechanical Measures

Quantifying muscular effort (or metabolic cost associated with producing muscle tension) during a wide range of human activities with a reliable and valid method has proven a significant challenge to biomechanists. As a result, researchers attempted to identify those biomechanical quantities that might correlate with metabolic factors (e.g. VO_2, heart rate, blood lactate). Andrews (1983) proposed two general types of biomechanical quantities to measure muscular effort: instantaneous and interval measures. Instantaneous measures occur at a particular instant in time (t) such as force, torque, and power values. Interval measures occur during a time interval of interest such as average force, torque, and power values, and linear and angular impulses. Periodically, effort has been quantified in the motor control literature using these measures.

A number of studies have examined perceived exertion (PE) with various types of muscular contractions involving the lower extremity (Pincivero, Coelho, Campy, Salfetnikov, & Bright, 2001; Pincivero et al., 2000; Pincivero et al., 2003). These authors also analyzed the effects of gender on perceived exertion. The first experiment by Pincivero et al. (2000) involved measuring torque in thirty subjects (*n* = 15 males and females) during isometric contraction of their quadriceps muscle. They sought to examine the validity and accuracy of the CR-10 scale and determine whether gender affects PE at specified contraction intensities. Subjects performed muscular contractions at specified intensities of their maximum voluntary contraction (MVC) and rated PE with a visual CR-10 scale. The results indicated that PE fit both linear and quadratic trends across the specified intensities. Also, no gender differences were found in PE across the levels of exercise intensity. The authors concluded that the CR-10 scale is a valid tool in assessing PE during this type of exercise and the scale is not gender specific.

As a continuance of the PE research, Pincivero et al. (2001) again sought to examine effort using quadriceps muscular contraction. However, this experiment involved 30 subjects (*n* = 15 male and female) performing concentric muscular contractions using the isokinetic dynamometer. Subjects performed five maximal isokinetic contractions to determine their single highest peak torque. Subjects then performed a specific % MVC by matching a line on a computer that represented their peak torque. Subjects rated PE using the CR-10 scale. The results indicated that the increase in PE across the contraction intensities fit both linear and quadratic trends. The authors concluded that PE is underestimated with submaximal isokinetic exercise and no gender difference exists in PE.

A third study by Pincivero et al. (2003) sought to examine gender differences in kinetic variables produced by knee extensor and flexor torque. Subjects (n = 19 male, n = 20 female) performed concentric knee extension and flexion muscular contractions using an isokinetic dynamometer. Subjects performed thirty reciprocal contractions to determine the knee extensor peak torque, work and power for each repetition. Statistical analysis and mathematical calculations determined quadriceps femoris muscle fatigue. Males produced greater peak torque, work, and power, both relative and absolute. Males demonstrated higher fatigue rates than females. Males demonstrated a greater predisposition to muscle fatigue than females, likely due to an inherent ability to generate greater knee and extensor torque (Pincivero et al., 2003). Researchers also have examined effort during movements involving the upper extremities.

Hasan (1986) suggested that effort was equated to the intensity of the central neural drive during upper-limb movements. Also, Rosenbaum and Gregory (2002) developed a protocol for relating the perception of effort to kinematic and kinetic measures during dynamic upper limb movements. They reported intra-class correlation coefficients (ICC) for angular displacement, peak angular velocity, and peak angular acceleration associated with varying effort levels ranged between r = 0.93 to 0.97. Also, the validity coefficient between net joint torque and effort level across varying movement frequencies was r = 0.86. Thus, this methodology is a reliable and valid method for measuring movement-related effort.

Lampropoulou and Nowicky (2011) used an 11-point Numeric Rating Scale (NRS) during an isometric elbow flexion task, where the end points signified either no effort (0) or maximal effort (10). Using a visual target marker with no numerical cues, subjects performed isometric elbow flexion at a specified level of MVC. Following the isometric muscle action, subjects rated perceived effort using the NRS. During the task, researchers collected force and surface electromyography (sEMG) data. The authors described power function ($y = ax^b$) relationships between effort ratings and both force and sEMG. Based upon acceptable ICC (r = 0.96 to 0.99) and constant relationships between effort and biomechanical parameters, the NRS is considered a valid and reliable scale for rating perception effort in healthy persons (Lampropoulou & Nowicky, 2011).

During isometric elbow flexion movements of the right upper extremity (dominant limb except one subject), perceived effort, as measured using a 0-10 Numeric Rating Scale (NRS), increased with the intensity of the voluntary muscular contraction (Lampropoulou & Nowicky, 2011). Also, the perception of effort increased with normalized surface electromyography (sEMG) activity of the biceps brachii, brachialis, and brachioradialis (Lampropoulou & Nowicky, 2011). Dynamic movement of the upper limbs during a chest press exercise at varying effort levels (25%, 50%, 75%, and 100% MVC) showed that perceived effort increased with the level of force produced by muscular contraction (Jackson & Dishman, 2000). Additional research examining the effects of varying loads (light = 0 kg; medium 1.2 kg; heavy = 2.4 kg) on perceived effort during dynamic single-joint upper extremity movements found that sense of effort was proportional to the external load (Moodie, 2007). As the external load increased, the elbow flexor and extensor muscle groups produced larger joint torques, thus intensifying movement-related effort.

2.4.2 Bilateral Force Deficit

Bilateral force deficit (BFD) is defined as the reduced force production during a unilateral muscular contraction as compared to a bilateral (homologous and contralateral groups) muscular contraction, during either maximal or submaximal contractions (Kuruganti, Murphy, & Pardy, 2011; McLean, Vint, & Stember, 2006). The summed unilateral force exceeds the bilateral force production, hence a resultant deficit. BFD has been demonstrated in both upper and lower extremities, both males and females, and at various levels of physical training (Archontides & Fazey, 1993; Bobbert, de Graaf, Jonk, & Casius, 2006; Kuruganti et al., 2011; McLean et al., 2006). Also, BFD exists in older populations (Hernandez, Nelson-Whalen, Franke, & McLean, 2003; Owings & Grabiner, 1998). Bilateral force deficit is present at submaximal as well as maximal effort levels (Kuruganti et al., 2011; McLean et al., 2006). Previous studies have shown bilateral force deficit during isometric elbow flexion and extension tasks (Ohtsuki, 1983). Deficits in bilateral force production constitute a significant performance-limiting factor during upper and lower extremity movements.

Kuruganti et al. (2011) collected force and EMG data during unilateral and bilateral isometric knee extension at three joint angles (0°, 45°, and 90°). The bilateral deficit was measured only during contractions at the 45° joint angle suggesting the muscle force-length relationship influences the muscular deficiency. EMG activity in the antagonistic muscles during unilateral and bilateral contractions was similar. These findings indicate that the force deficit is not due to changes in antagonistic muscle activity (Kuruganti et al., 2011).

McLean et al. (2006) measured force and EMG activity during unilateral and bilateral isometric elbow flexion. Subjects performed the elbow tasks at specified effort levels relative to percentages of their MVC. Absolute bilateral force deficits ranged from -16% at submaximal effort (25% of maximal effort) to -10% at maximal effort (100% of maximal effort). During submaximal intensity levels, perception of effort for bilateral tasks was significantly higher ($p < 0.01$) than corresponding unilateral tasks. Thus, perceptual and physiological factors influence bilateral deficit at submaximal effort levels (McLean et al., 2006).

2.4.3 Handedness

Dominant and non-dominant arm movements use distinct neural control mechanisms. During reaching tasks with right-handed subjects, final position accuracy was similar for both hands, but hand trajectories and joint coordination patterns during the movements were systematically different (Sainburg & Kalakanis, 2000). Handedness reflects cerebral specialization for specific control processes. According to Sainburg (2005), each hemisphere/limb system is specialized for different but complementary functions: the dominant system for controlling limb trajectory dynamics and the non-dominant system for controlling limb position.

Previous literature supports differences in biomechanical parameters between dominant and non-dominant limbs during dynamic movements. Throughout limb movements, there are dynamic interactions between the joints of the moving limb, described as intersegmental interaction torque (INT) (Bagesteiro & Sainburg, 2002;

Sainburg, 2005). Passive INT is required for coordination of movements involving multiple segments (Dounskaia, 2010). Other biomechanical quantities described as contributing to joint torque include net torque (NET) and muscular torque (MUS) (Dounskaia, 2010). Thus, the NET joint torque represents the summative values of INT and MUS, assuming a rigid body model (Bagesteiro & Sainburg, 2003).

While performing a reaching task involving two joints (shoulder and elbow), the dominant arm motions produced approximately 50% less MUS as compared to the non-dominant limb (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). The non-dominant limb demonstrated larger MUS influences to NET, and thereby, less efficient movements (Sainburg, 2005). Also, the chosen pathway when reaching for a target varies between the dominant and non-dominant arms. The dominant arm moves in gently curved medial to lateral direction, while the non-dominant path is largely straight (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000).

This difference in reaching paths influences shoulder and elbow kinematics, along with limb kinetics. Biomechanical analysis of the dominant limb revealed greater shoulder flexion elbow, producing considerable elbow INT. For the dominant limb, elbow MUS provided about 50% to elbow NET, while INT provided the other 50% (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). Because of the straight line path taken by the non-dominant limb, there was minimal shoulder motion, and, as a result, almost the entire movement was generated by elbow MUS (Bagesteiro & Sainburg, 2002; Sainburg, 2005). This non-dominant force profile is thought to represent a less torque-efficient control strategy (Sainburg, 2005). Thus, a less efficient control strategy during non-dominant arm movements may be perceived as increased effort.

2.5 Summary

Human movement is a complex phenomenon requiring further analysis and explanation. Within the field of biomechanics, researchers attempted to solve the infinite degrees of freedom dilemma (Bernstein problem) involving human movement. According to Andrews (1983), several kinematic and kinetic parameters may be associated with effort, but this claim was not validated. Using biomechanical parameters, the current study quantified the effects of task on movement-related effort during dynamic elbow joint movements. Specifically, this research project examined how movement-related effort changed between unilateral and bilateral movements involving the elbow joint.

CHAPTER 3

METHODS

3.1 Subjects

Ten healthy, young (20-40 years of age), right-hand dominant males participated in the study. As shown in Table 1, demographic data was collected for each of the subjects participating in the experiment. We obtained approval for this study from The University of Kansas Human Subject Committee of Lawrence prior to subject recruitment and testing. After a brief overview of the study, each subject provided informed consent (see Appendix A) prior to participation in the study. Subjects were screened to exclude potential health problems including cardiovascular, musculoskeletal, and/or neurological diseases (see Appendix B). A standardized handedness questionnaire (see Appendix C) determined the hand dominance of each subject (Chapman & Chapman, 1987). Subjects visited the lab on two occasions; the first visit for about 30 minutes and the second visit for approximately 60 minutes.

Table 3.1.

Subject Characteristics

Characteristic	**Mean ± SD**	**Range**
Age (yr)	30.4 ± 7.6	23-43
Height (m)	1.8 ± 0.07	1.7-1.9
Mass (kg)	87.9 ± 16.8	69.1-113.7

Note. *N* = 10. yr = years; m = meters; kg = kilograms.

3.2 Experimenta l Protocol

During the first visit, the testing protocol investigated movement-related effort during dynamic elbow flexion and extension tasks. Subjects began the first session by performing a 5-minute warm-up exercise (arm cranking) using an upper body ergometer (881E; Monark Exercise AB, Vansbro, Sweden). Following the warm-up, subjects were seated in an isokinetic dynamometer (Kin-Com 125AP; Chattanooga Group, Inc., Chattanooga, TN) in an upright position so that the elbow flexion and extension movements occurred in the horizontal plane; elbow joint angles of 45° through 135° were used as these angles represent a typical dynamic elbow active range of motion (AROM).

Subjects performed two repetitions of dynamic elbow flexion and extension at specified levels of maximal voluntary contraction (MVC). For each specified trial, torque values were collected using a dynamometer (KinCom 125AP; Chattanooga Group, Inc., Vista, CA). The dominant upper extremity was tested first, followed by the non-dominant upper extremity. The collection of elbow flexion and extension joint torques occurred at four specified levels of effort. Subjects performed a voluntary isokinetic contraction of their elbow flexors and extensors at 180°/second corresponding to an effort level of 25%, 50%, 75%, or 100% MVC. A series of sounds that constituted a, “one, two, three, go” signaled the start of each trial. Separation of each sub-maximal trial by 30 seconds of rest minimized fatigue in the subjects; the subjects had 3 minutes of rest between the 100% MVC’s.

During the second visit, subjects performed dynamic elbow flexion and extension tasks according to specified effort levels. Subjects began the second session by performing a 5-minute warm-up exercise (arm cranking) using an upper body ergometer (881E; Monark Exercise AB, Vansbro, Sweden). Following the warm-up, subjects sat in front of a high-density polyethylene-coated table as shown in Figure 1. Subjects positioned their chests resting comfortably against the table. Subjects elevated their upper limb relative to the table by placing the extremity on a foam pad; this position permitted the elbow joint to move unhindered throughout the range of motion. The glenohumeral joint remained fixed in approximately 90° of flexion and 45° of horizontal abduction during the elbow movements. Subjects grasped a plastic dowel capable of sliding on the surface of the polyethylene table. In order to minimize friction between the table and the dowel, the bottom of the plastic dowel was coated with Teflon®.

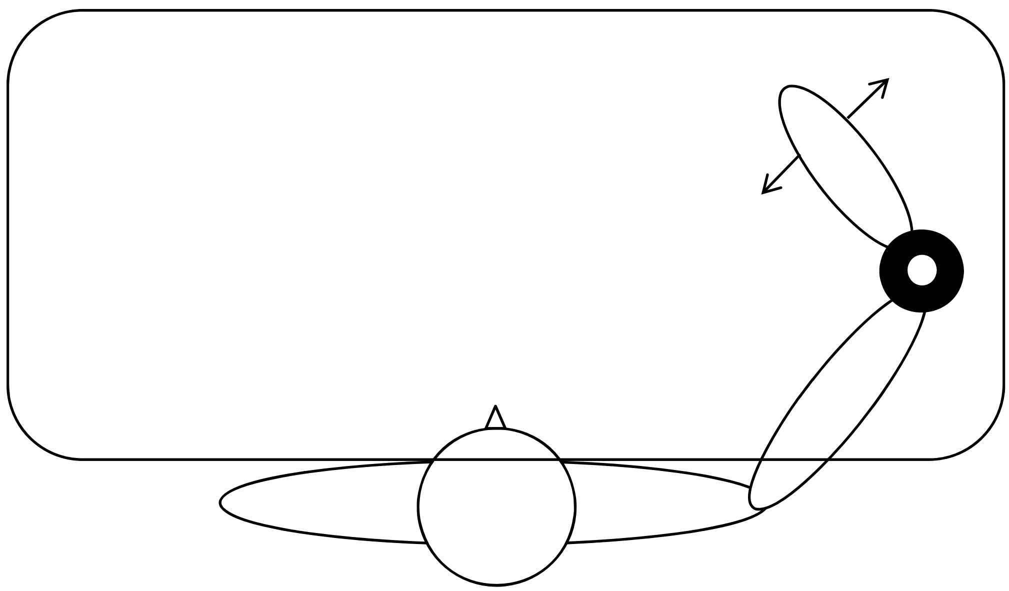

Figure 3.1. Schematic drawing of the experimental setup.

Subjects produced elbow flexion and extension movements in the horizontal plane for 30 movement cycles. Subjects performed a voluntary contraction of their elbow flexors and extensors that corresponded to effort level ratings of 1, 3, 5, 7, or 9, on a modified Borg CR-10 scale, such that 0 = "no effort" and 10 = "maximal effort" (see Figure 2). Subjects performed movements at each of the five effort levels with their upper extremity in four conditions: unilateral dominant, unilateral non-dominant, bilateral in-phase, and bilateral anti-phase; movements were produced at frequency of 2 Hz. Testing of 20 movement conditions (5 effort levels x 4 tasks) occurred in random order. Subjects performed one trial of each condition in two separate rounds of testing. The first series of elbow contractions allowed familiarization of the expected movement, while data acquisition occurred during the second series of contractions. Separation of each trial by 90 seconds of rest minimized fatigue in the subjects.

0 – No effort

1 – Very Light

2

3 – Light

4

5 – Moderate

6

7 – Strong

8

9 – Very Strong

10 – Maximal Effort

Figure 3.2. Effort rating scale.

An active optical motion capture system (Visualeyez VZ3000; PhoeniX Technologies, Inc., Burnaby, Canada) quantified angular displacement of the elbow joint relative to the stationary upper arm at sampling frequency of 200 Hz. Wireless light-emitting diode markers placed on the subject's wrist (radial aspect) and elbow (lateral humerus) captured the relative motion of the forearm with respect to the stationary arm. A metronome created using the LabVIEW software (Version 6.0; National Instruments, Austin, TX) signaled the required movement frequency. The metronome signaled twice during each movement cycle such that it beeped with each movement direction reversal.

At the start of each trial, each subject positioned their forearm at the mid-range of elbow joint flexion and extension range of motion. Following subject positioning, the experimenter indicated the required effort level for the specified trial, waited for the subject to repeat it, and began data acquisition. Subjects listened to the metronome as long as necessary to "get the feel" of the required movement frequency. Subjects commenced movement in the direction of flexion at their own discretion. After initiation of the movement, 30 elbow flexion and extension movement cycles were recorded. Subjects moved the elbow joint through any desired range of motion as long the movement corresponded with the assigned effort level and frequency established by the metronome.

3.3 Analysis

Wireless light-emitting diodes captured the angular position of the forearm with respect to the stationary arm; this information provided angular position-time series data. VZDaq software (Version 1.0; PhoeniX Technologies, Inc., Vancouver, Canada) gathered the kinematic data. Time and position data collected from the motion capture software were placed into an Excel (Microsoft Excel 2010; Microsoft Corporation, Redmond, WA) spreadsheet; this raw data was then smoothed using a Butterworth 4^{th}-order zero-lag filter. Kinematic (angular displacement, peak angular velocity, peak angular acceleration) and kinetic quantities (peak joint torque) were derived from the position-time series data.

In order to minimize movement initiation and termination effects, data analysis did not include the first 10 and last 10 movement cycles. Calculation of the biomechanical parameters arose from the 10 middle cycles of the flexion and extension movements. A Visual Basic program (Version 6.0; Microsoft Corporation, Redmond, WA) located the peak values (instantaneous measures) for flexion and extension movements. For each trial, mean values of the individual cycles were calculated for velocity and acceleration. After data processing, average values for each subject (n = 10) were compiled into a database (see Appendix E). Kinetic and kinematic variables were calculated according to standard methods (Winter, 2009; Zatsiorsky, 2002).

PJT values were calculated based upon the premise that net joint torque (T_{net}) represents the sum of the elbow flexor/extensor torque to move mass (T_{elbow}) plus the elbow flexor/extensor torque to overcome friction between handle/table ($T_{friction}$). Using established anthropometric data (Winter, 2009), the moment of inertia (I) of the forearm/hand about the elbow joint was calculated for each subject. Angular acceleration (α) values of forearm/hand about the elbow joint for each subject were obtained from the motion capture analysis. Using a known equation, the elbow joint torque (T_{elbow}) to move the segment is represented by the product of I and α. Again, using established anthropometric data (Winter, 2009) and the accepted coefficient of friction for plastics, the handle moment of inertia (I) and the frictional force ($F_{friction}$) were computed. Using a known equation, the elbow joint torque ($T_{friction}$) to overcome friction was represented by the product of the $F_{friction}$ and the moment arm (ma). Thus, with known values for T_{elbow} and $T_{friction}$, the value for T_{net} was calculated.

Kinematic variables including PAV and PAA were calculated using an accepted biomechanical approach named the first central difference method (Hamill & Knutzen, 2009). This method corrects for potentially unmatched time/position data by using the difference in angular positions over two frames as the numerator. The denominator in the velocity calculation becomes the change in time over two intervals. Using the position-time series data collected from the motion capture system, angular velocity (ω_i) was calculated via the following formula (Hamill & Knutzen, 2009):

$$\omega_i = \Theta_{i+1} - \Theta_{i-1}/t_{i+1} - t_{i-1}. \qquad (1)$$

In equation (1), Θ_i is the angle at time t_i. Thus, the first central method calculates the angular velocity at the same instant at which the data for angular position are available.

Angular acceleration (α_i) is the derivative of angular velocity (ω_i). Again, the first central method was used to calculate angular acceleration via the following equation (Hamill & Knutzen, 2009):

$$\alpha_i = \omega_{i+1} - \omega_{i-1}/t_{i+1} - t_{i-1}. \qquad (2)$$

In equation (2), ω_i is the angular velocity at time t_i. Thus, ω_i and α_i were calculated using the same biomechanical methods.

A three-way analysis of variance (ANOVA) analyzed the effects of task (unilateral, bilateral in-phase, bilateral anti-phase) arm (dominant, non-dominant), and effort level (1, 3, 5, 7, 9) on kinematic and kinetic parameters. If significant differences were found using ANOVA, *post hoc* analysis identified the specific effect of task, arm and effort level using paired *t*-tests with a Bonferroni correction for multiple comparisons. The level of significance was set at $\alpha = 0.05$. The statistical analyses of the data were performed using SPSS 15.0 software (SPSS Inc., Chicago, IL).

CHAPTER 4

RESULTS

Overall, the results indicated that the kinematic (MAD, PAV, PAA) and kinetic (PJT) parameters changed as a function of effort and task. Plots of the results for this experiment (see Figures 4.1 – 4.15) indicated a common trend for the biomechanical variables. Generally, the plots depicted that as effort level increased, the biomechanical quantities became larger. Also, as task (unilateral, bilateral in-phase, bilateral anti-phase) changed, the biomechanical variables demonstrated a consistent relationship largely supporting the previously described hypotheses. However, further elaboration of these findings will be outlined in the subsequent sections.

4.1 Angular Displacement

Angular displacement results for this experiment are shown in Figure 4.1. Angular displacements (mean ± SD) for the unilateral task ranged from 14.6° ± 7.8° to 89.1° ± 14.3° and from 14.4° ± 8.0° to 84.2° ± 11.5° for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.2).

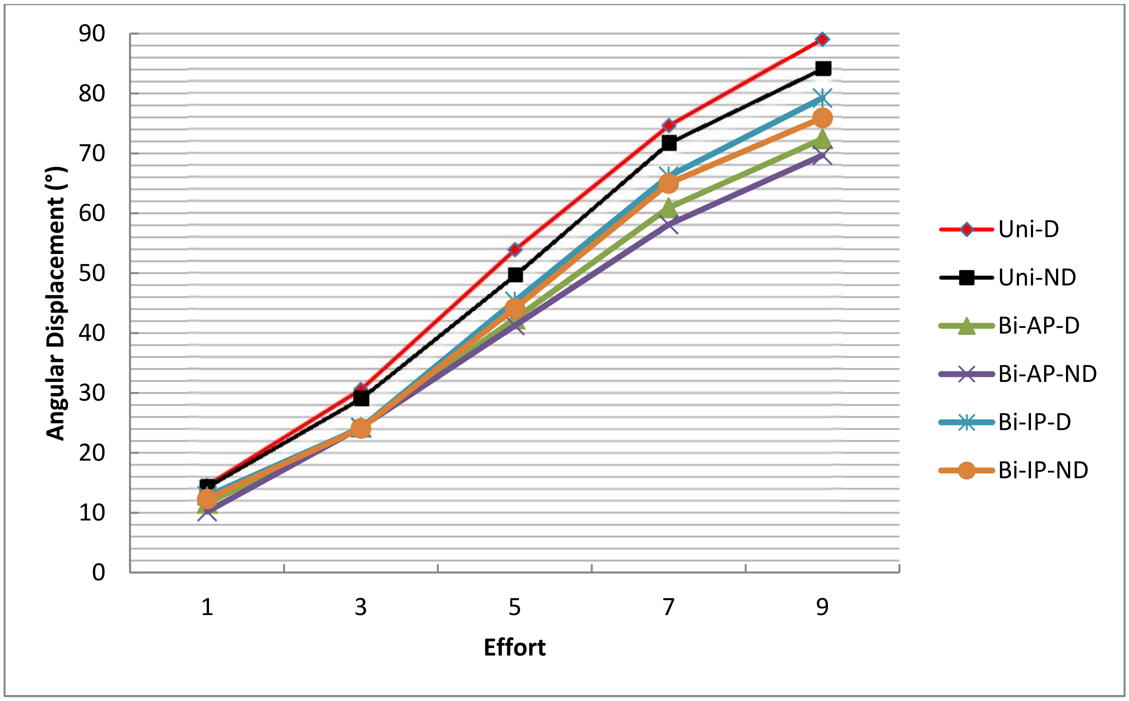

Figure 4.1. Angular displacement (mean) versus effort for the unilateral and bilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; ° = degrees.

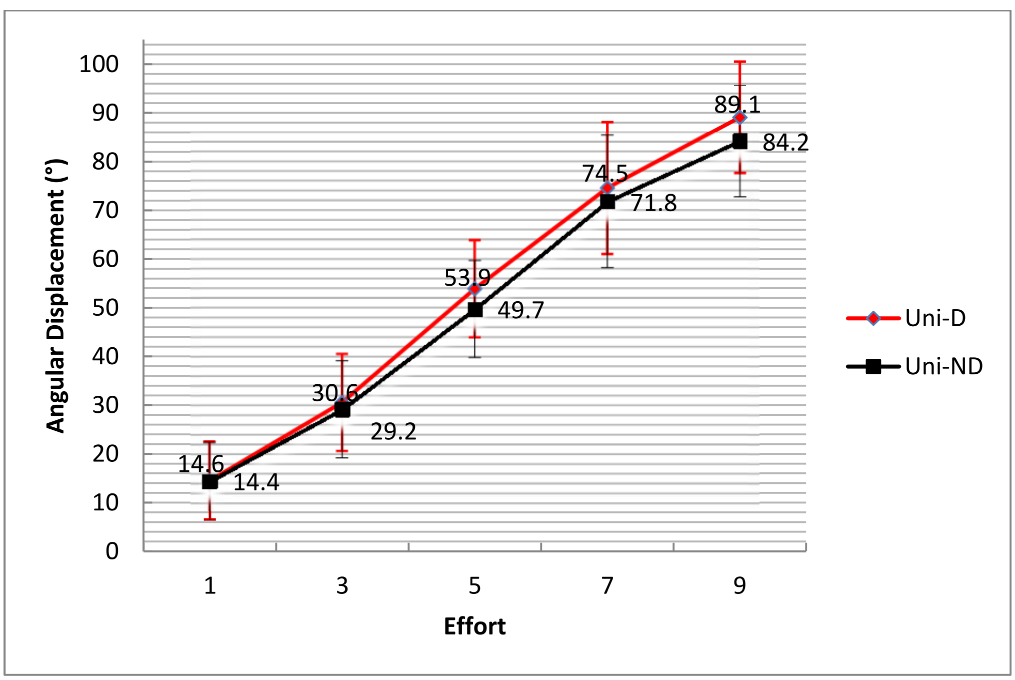

Figure 4.2. Angular displacement (mean ± SD) versus effort for the unilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; ° = degrees.

For the bilateral/in-phase task, angular displacements ranged from 12.8° ± 7.8° to 79.2° ± 12.0° and from 12.3° ± 7.2° to 75.9° ± 11.1° for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.3). For the bilateral/anti-phase task, angular displacements ranged from 11.6° ± 6.9° to 72.4° ± 12.4° and from 10.2° ± 6.4° to 69.7° ± 11.6° for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.4).

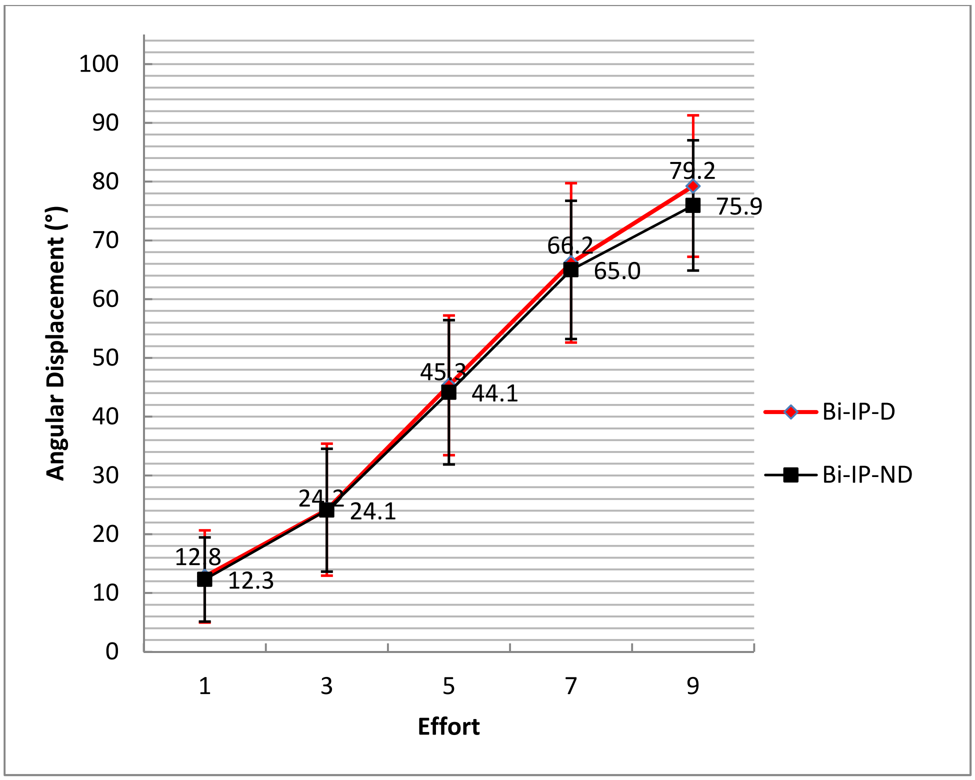

Figure 4.3. Angular displacement (mean ± SD) versus effort for the bilateral/in-phase tasks. Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; ° = degrees.

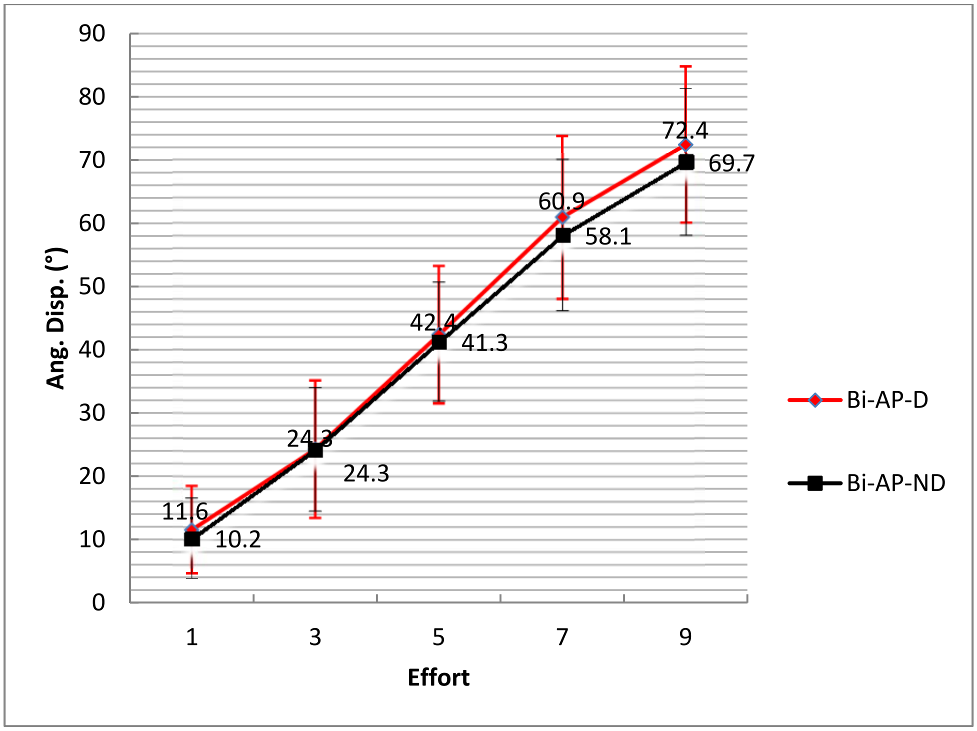

Figure 4.4. Angular displacement (mean ± SD) versus effort for the bilateral/anti-phase tasks. Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; ° = degrees.

There was a significant main effect of task on angular displacement ($F_{2,8} = 40.04$, $P < 0.0001$). Across all effort levels, the subjects produced significantly greater angular displacement during unilateral tasks than bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms. There was also a significant main effect of arm on angular displacement ($F_{1,9} = 6.72$, $P < 0.05$). For the unilateral task, the subjects produced significantly greater angular displacements during the dominant arm condition as compared to the non-dominant arm condition across all effort levels. In addition, there was a strong trend for greater angular displacement during the dominant arm condition as compared to the non-dominant arm condition during the bilateral tasks (both in-phase and anti-phase) across all effort levels; however, this difference was not statistically significant. Finally, the main effect of effort level on angular displacement was significant ($F_{4,6} = 103.70$, $P < 0.0001$). For each increase in effort level, the subjects produced significantly greater angular displacement during the unilateral and bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms.

There were two significant interaction effects across the main effects of task, arm, and effort level. The interaction between task and effort level was significant ($F_{8,2}$ = 10.92, $P < 0.0001$). Across all effort levels, greater angular displacement was produced during the unilateral task conditions than the bilateral (in-phase and anti-phase) task conditions for the dominant and non-dominant arms. While there were no differences in angular displacement between the bilateral/in-phase and bilateral/anti-phase task conditions for effort levels 1, 3, and 5, angular displacement was significantly larger for the bilateral/in-phase task condition than the bilateral anti-phase task condition for effort levels 7 and 9. The interaction between arm and effort level was also significant ($F_{4,6}$ = 4.05, $P < 0.01$). Across all three tasks, the dominant arm produced larger angular displacements than the non-dominant arm; the difference between the dominant and non-dominant arms increased as a function of effort level (a 0.67° ± 0.17° difference at effort level 1 to a 3.65° ± 0.64° difference at effort level 9). The interaction effects between task and arm across all effort levels ($F_{2,8}$ = 0.97, P = 0.398) and between task, arm, and effort level ($F_{8,2}$ = 0.59, P = 0.78) were not significant.

4.2 Angular Velocity

Angular velocity results for this experiment are shown in Figure 4.5. Angular velocities (mean ± SD) for the unilateral task ranged from 92.3°/s ± 50.5°/s to 583.6°/s ± 114.1°/s and from 92.2°/s ± 49.3°/s to 551.7°/s ± 126.9°/s for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.6).

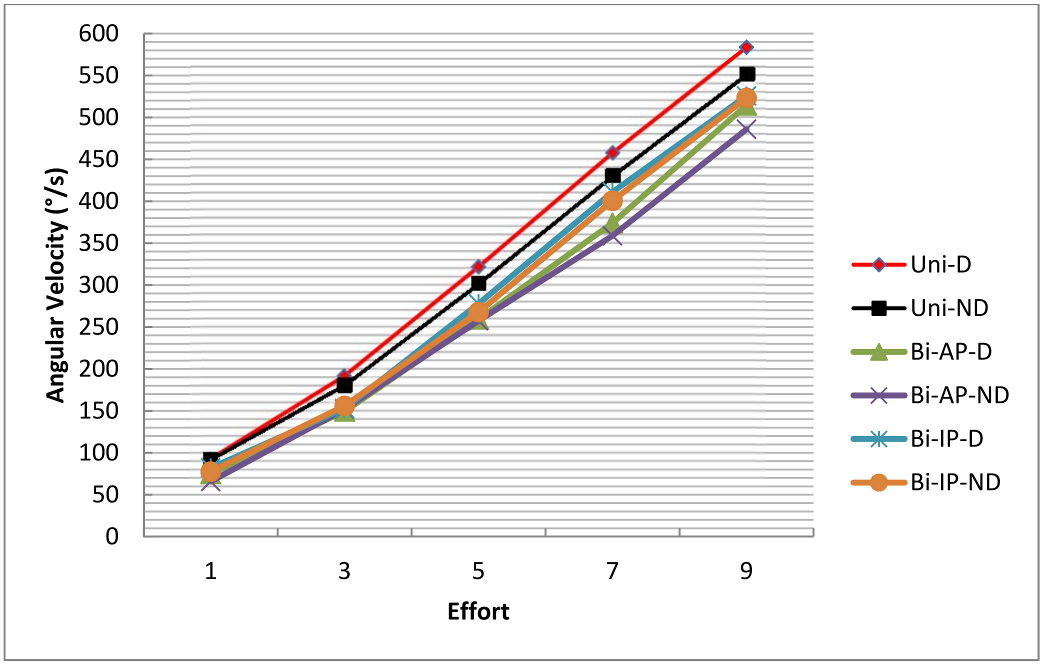

Figure 4.5. Angular velocity (mean) versus effort for the unilateral and bilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; °/s = degrees/second.

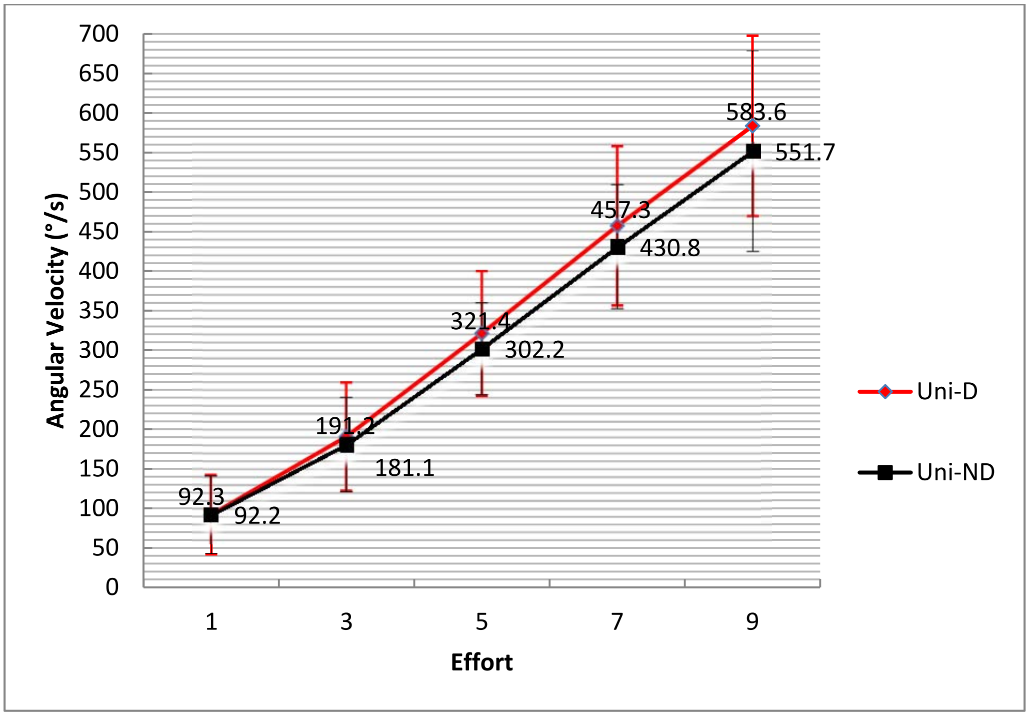

Figure 4.6. Angular velocity (mean ± SD) versus effort for the unilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; °/s = degrees/second.

For the bilateral/in-phase task, angular velocities ranged from 81.9°/s ± 48.9°/s to 525.6°/s ± 107.3°/s and from 77.5°/s ± 44.0°/s to 523.3°/s ± 110.0°/s for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.7). For the bilateral/anti-phase task, angular velocities ranged from 74.9°/s ± 44.2°/s to 514.6°/s ± 132.8°/s and from 65.8°/s ± 40.2°/s to 486.0°/s ± 96.5°/s for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.8).

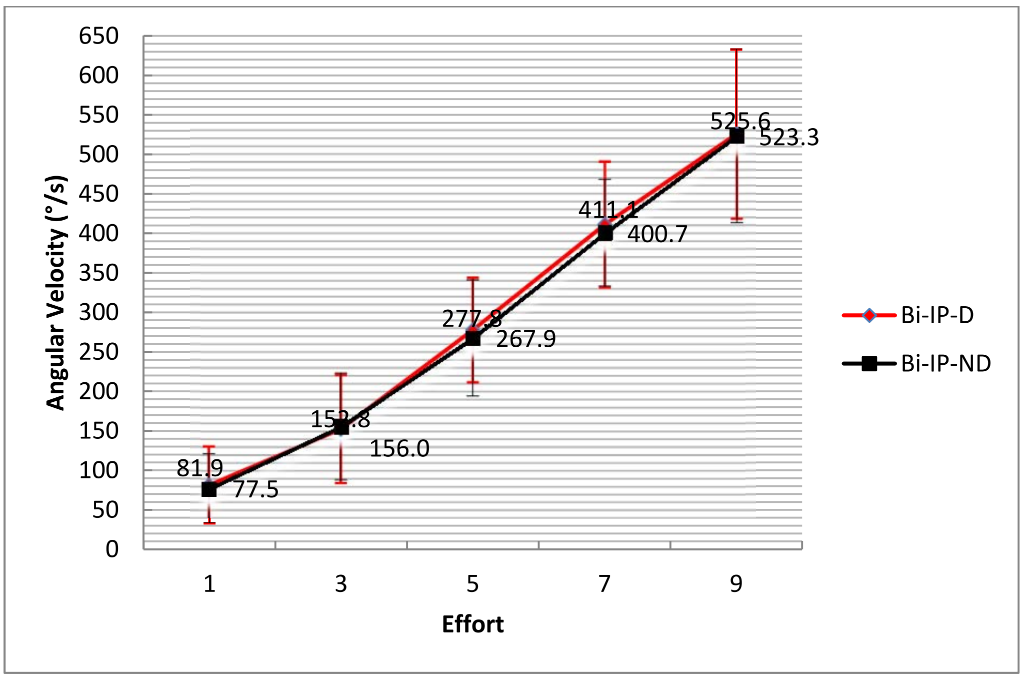

Figure 4.7. Angular velocity (mean ± SD) versus effort for the bilateral/in-phase tasks. Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; °/s = degrees/second.

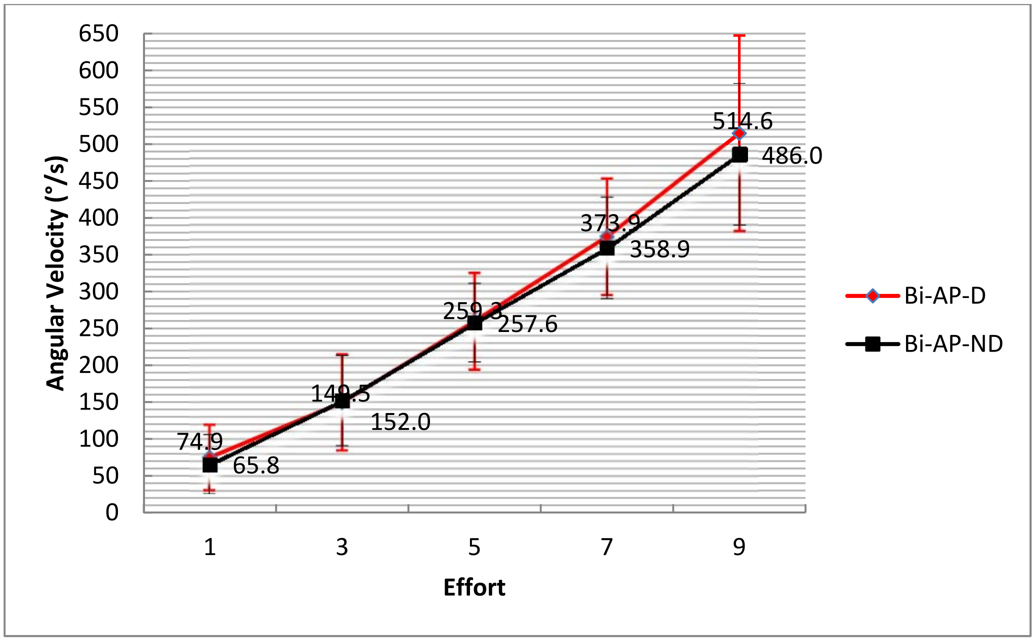

Figure 4.8. Angular velocity (mean ± SD) versus effort for the bilateral/anti-phase tasks. Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; °/s = degrees/second.

There was a significant main effect of task on angular velocity ($F_{2,8} = 27.54$, $P < 0.0001$). Across all effort levels, the subjects produced significantly greater angular velocity during unilateral tasks than bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms. There was also a significant main effect of arm on angular velocity ($F_{1,9} = 7.41$, $P < 0.05$). For the unilateral task, the subjects produced significantly greater angular velocities during the dominant arm condition as compared to the non-dominant arm condition across all effort levels. In addition, there was a strong trend for greater angular velocity during the dominant arm condition as compared to the non-dominant arm condition during the bilateral tasks (both in-phase and anti-phase) across all effort levels; however, this difference was not statistically significant. Finally, the main effect of effort level on angular velocity was significant ($F_{4,6} = 89.32$, $P <$

0.0001). For each increase in effort level, the subjects produced significantly greater angular velocity during the unilateral and bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms.

There were two significant interaction effects across the main effects of task, arm, and effort level. The interaction between task and effort level was significant ($F_{8,2} = 3.41$, $P < 0.005$). Across all effort levels, greater angular velocity was produced during the unilateral task conditions than the bilateral (in-phase and anti-phase) task conditions for the dominant and non-dominant arms. While there were no differences in angular velocity between the bilateral/in-phase and bilateral/anti-phase task conditions for effort levels 1, 3, and 5, angular velocity was significantly larger for the bilateral/in-phase task condition than the bilateral anti-phase task condition for effort levels 7 and 9. The interaction between arm and effort level was also significant ($F_{4,6} = 2.74$, $P < 0.05$). Across all three tasks, the dominant arm produced larger angular velocities than the non-dominant arm. The interaction effects between task and arm across all effort levels ($F_{2,8} = 1.23$, $P = 0.315$) and between task, arm, and effort level ($F_{8,2} = 0.48$, $P = 0.869$) were not significant.

4.3 Angular Acceleration

Angular acceleration results for this experiment are shown in Figure 4.9. Angular accelerations (mean ± SD) for the unilateral task ranged from $1335.5°/s^2 \pm 717.6°/s^2$ to $10088.6°/s^2 \pm 2413.2°/s^2$ and from $1319.8°/s^2 \pm 737.5°/s^2$ to $9662.1°/s^2 \pm 3281.2°/s^2$ for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.10).

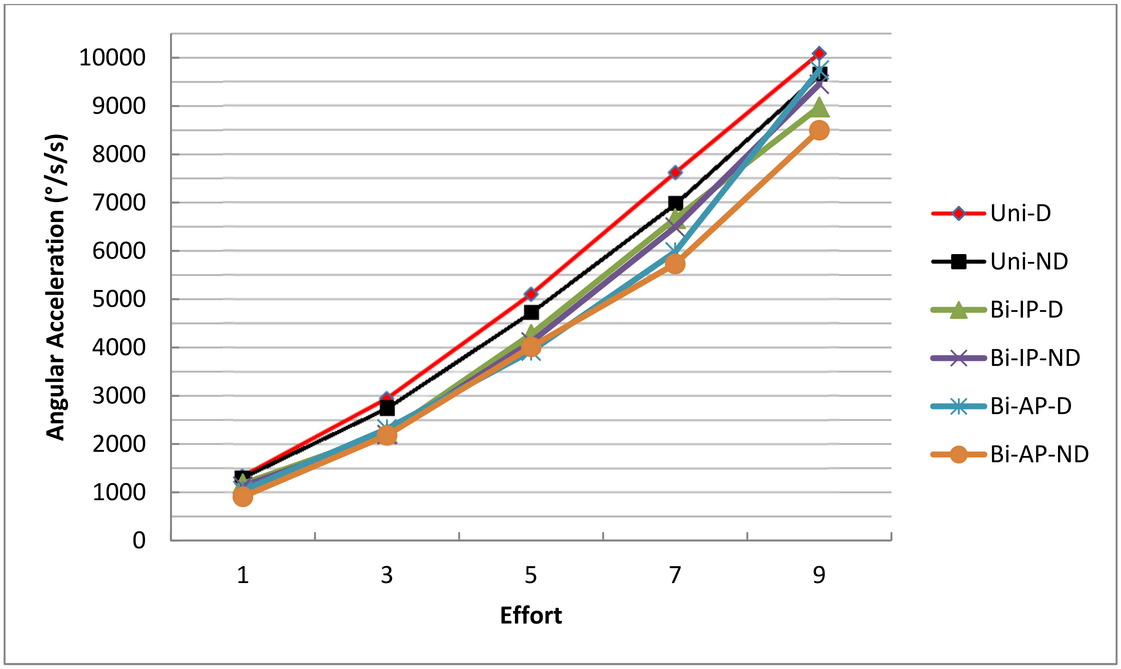

Figure 4.9. Angular acceleration (mean) versus effort for the unilateral and bilateral tasks. Uni-D = Unilateral Dominant; Uni-ND Unilateral Non-Dominant; Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; °/s/s = degrees/second/second.

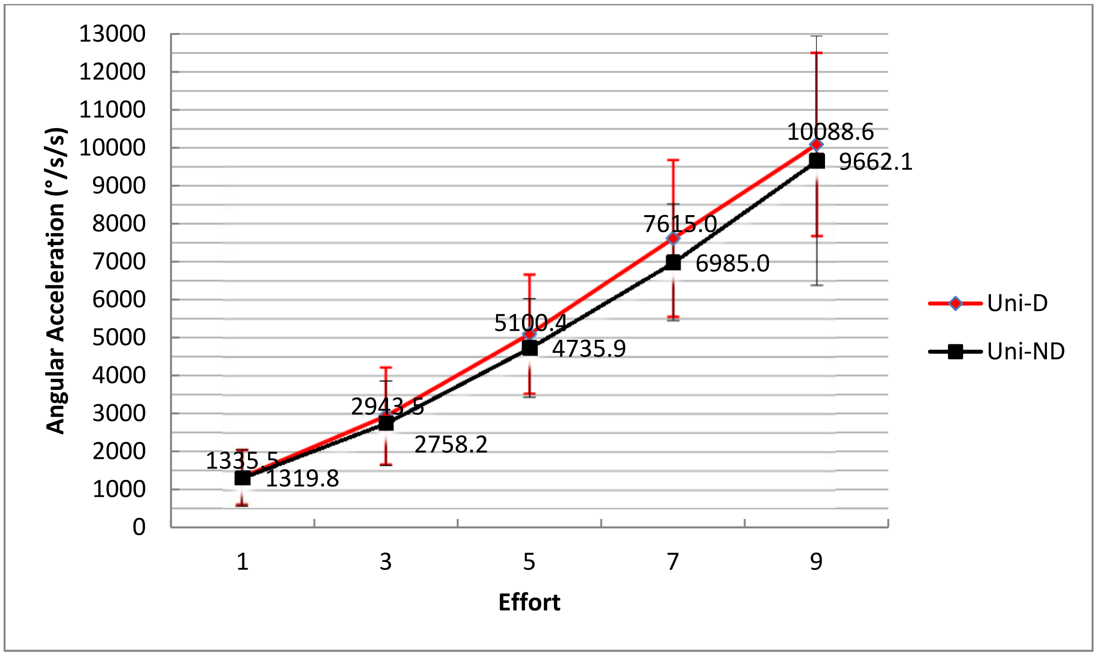

Figure 4.10. Angular acceleration (mean ± SD) versus effort for the unilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; °/s/s = degrees/second/second.

For the bilateral/in-phase task, angular accelerations ranged from 1179.8°/s^2 ± 690.6°/s^2 to 8982.3°/s^2 ± 2417.0°/s^2 and from 1128.6°/s^2 ± 673.6°/s^2 to 9452.7°/s^2 ± 3424.6°/s^2 for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.11). For the bilateral/anti-phase task, angular accelerations ranged from 1037.0°/s^2 ± 598.9°/s^2 to 9745.7°/s^2 ± 4378.3°/s^2 and from 908.3°/s^2 ± 521.4°/s^2 to 8502.0°/s^2 ± 2994.3°/s^2 for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.12).

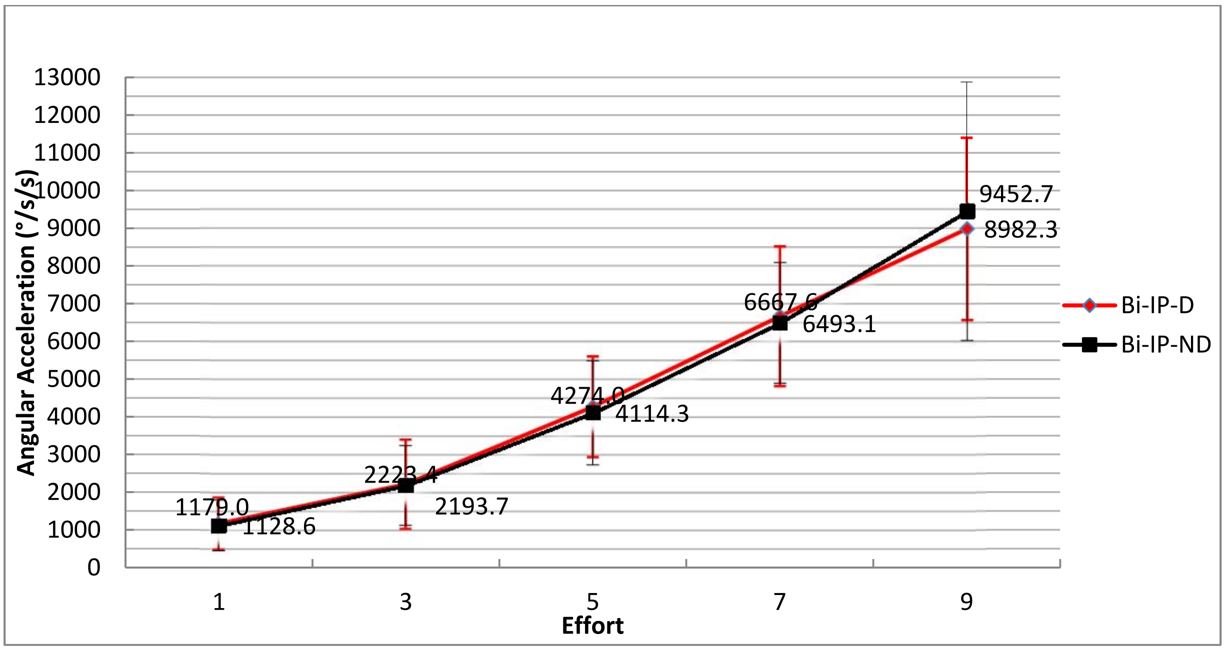

Figure 4.11. Angular acceleration (mean ± SD) versus effort for the bilateral/in-phase tasks. Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; °/s/s = degrees/second/second.

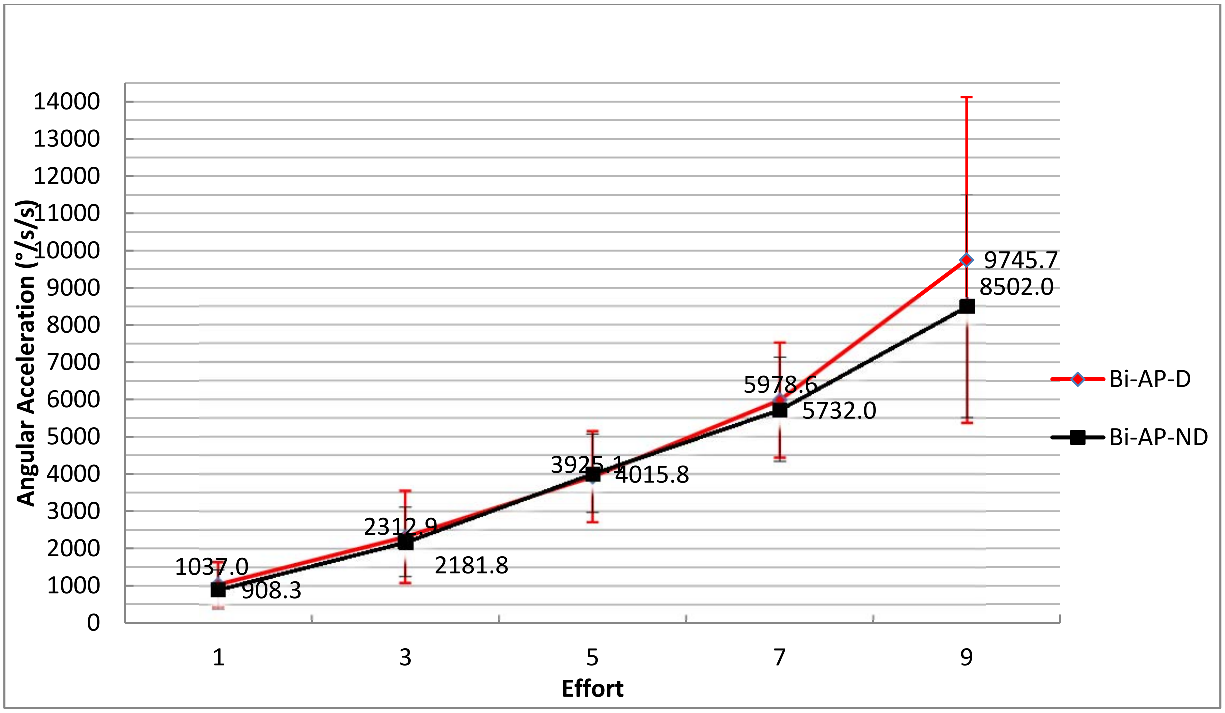

Figure 4.12. Angular acceleration (mean ± SD) versus effort for the bilateral/anti-phase tasks. Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; °/s/s = degrees/second/second.

There was a significant main effect of task on angular acceleration ($F_{2,8} = 15.22$, $P < 0.0001$). Across all effort levels, the subjects produced significantly greater angular acceleration during unilateral tasks than bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms. There was also a significant main effect of arm on angular acceleration ($F_{1,9} = 8.21$, $P < 0.05$). For the unilateral task, the subjects produced significantly greater angular accelerations during the dominant arm condition as compared to the non-dominant arm condition across all effort levels. In addition, there was a strong trend for greater angular acceleration during the dominant arm condition as compared to the non-dominant arm condition during the bilateral tasks (both in-phase and anti-phase) across all effort levels; however, this difference was not statistically significant. Finally, the main effect of effort level on angular acceleration was significant

($F_{4,6}$ = 56.34, $P < 0.0001$). For each increase in effort level, the subjects produced significantly greater angular acceleration during the unilateral and bilateral (in-phase and anti-phase) tasks for the dominant and non-dominant arms.

The interaction effects between task and effort across both arm conditions was not significant ($F_{8,2}$ = 1.47, P = 0.183). The interaction effects between task and arm across all effort levels ($F_{2,8}$ = 1.37, P = 0.281) and between task, arm, and effort level ($F_{8,2}$ = 1.36, P = 0.230) were not significant. Also, the interaction effects between arm and effort across all task conditions was not significant ($F_{4,6}$ = 1.37, P = 0.264).

4.4 Peak Joint Torque

Peak joint torque results for this experiment are shown in Figure 4.13. Peak joint torques (mean ± SD) for the unilateral task ranged from 9.8 ± 5.8 to 63.5 ± 20.7 N·m and from 9.8 ± 5.9 to 61.5 ± 28.0 N·m for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.14).

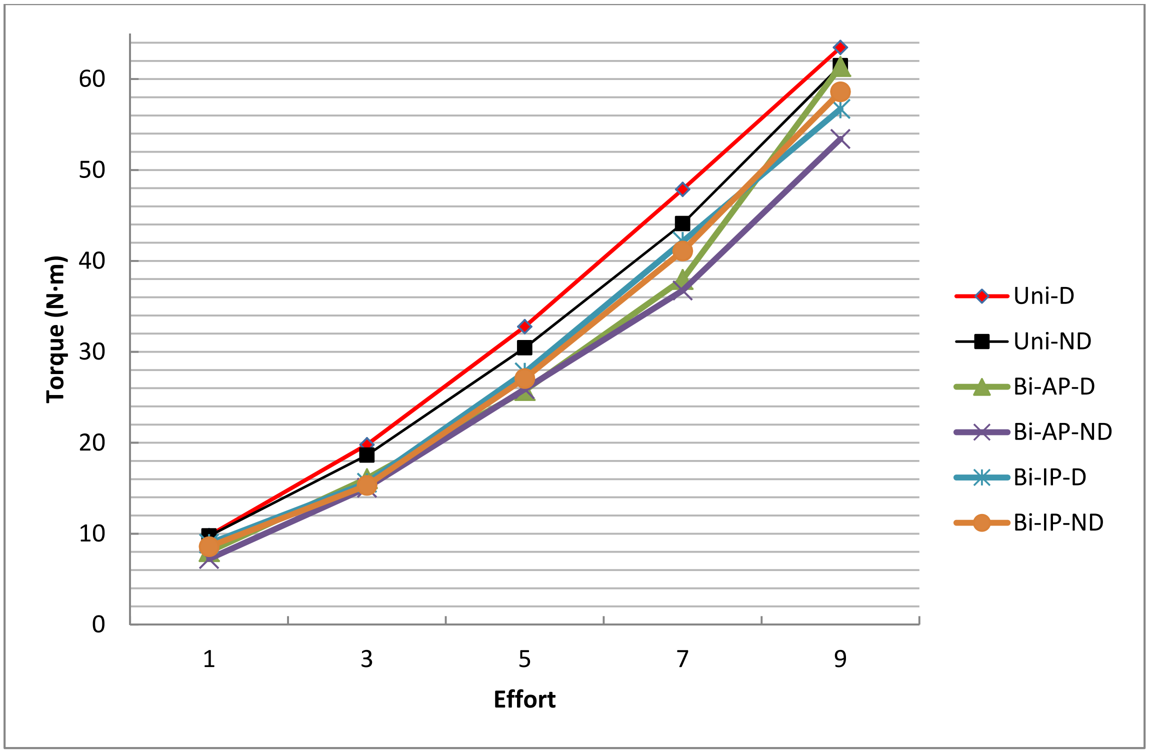

Figure 4.13. Elbow joint torque (mean) versus effort for the unilateral and bilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; N·m = Newton· meters.

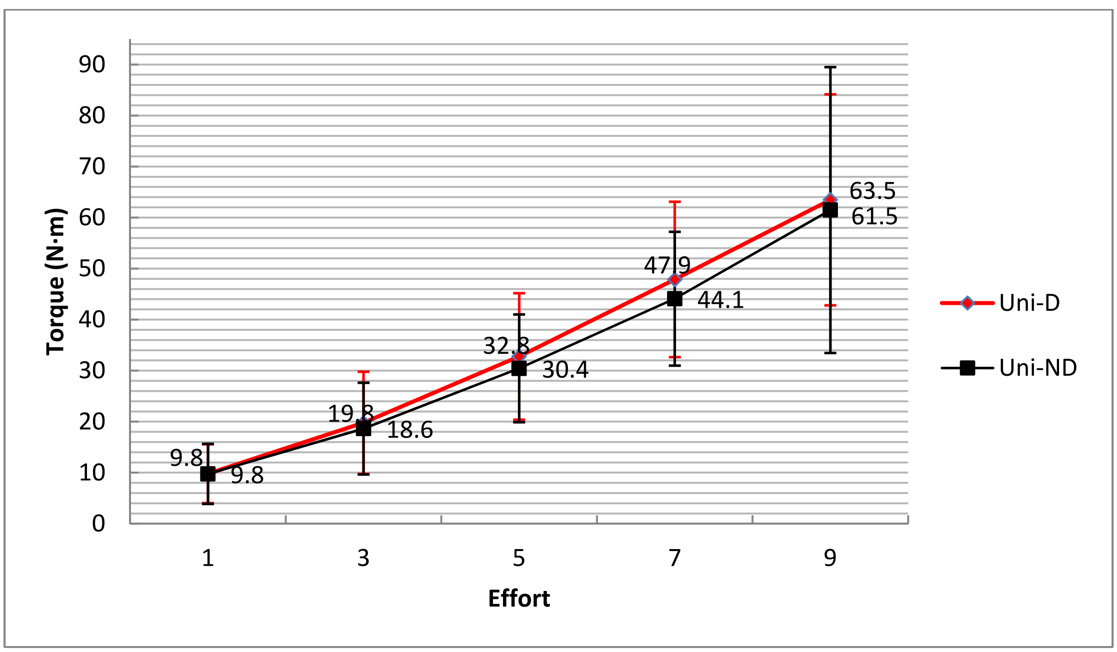

Figure 4.14. Elbow joint torque (mean ± SD) versus effort for the unilateral tasks. Uni-D = Unilateral Dominant; Uni-ND = Unilateral Non-Dominant; N·m = Newton· meters.

For the bilateral/in-phase task, peak joint torques ranged from 8.9 ± 5.8 to 56.7 ± 20.4 N·m and from 8.6 ± 5.6 to 58.6 ± 21.9 N·m for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.15). For the bilateral/anti-phase task, peak joint torques ranged from 8.0 ± 5.3 to 61.4 ± 18.3 N·m and from 7.2 ± 4.7 to 53.4 ± 22.5 N·m for the dominant and non-dominant arms, respectively, as the effort level increased from 1 to 9 (see Figure 4.16).

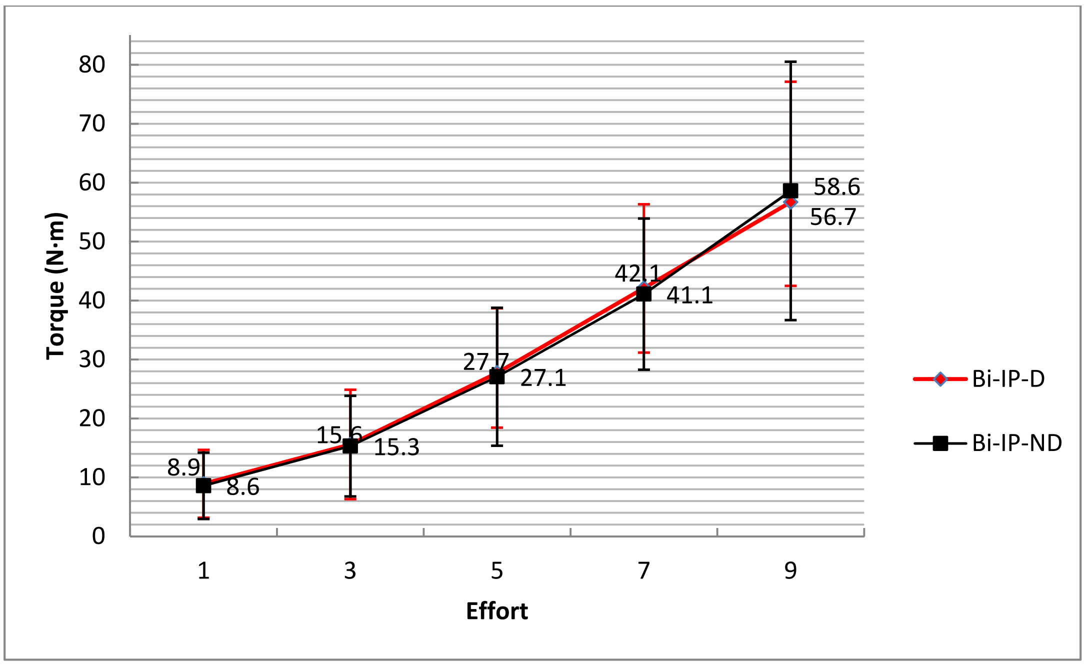

Figure 4.15. Elbow joint torque (mean ± SD) versus effort for the bilateral/in-phase tasks. Bi-IP-D = Bilateral In-Phase Dominant; Bi-IP-ND = Bilateral In-Phase Non-Dominant; N·m = Newton· meters.

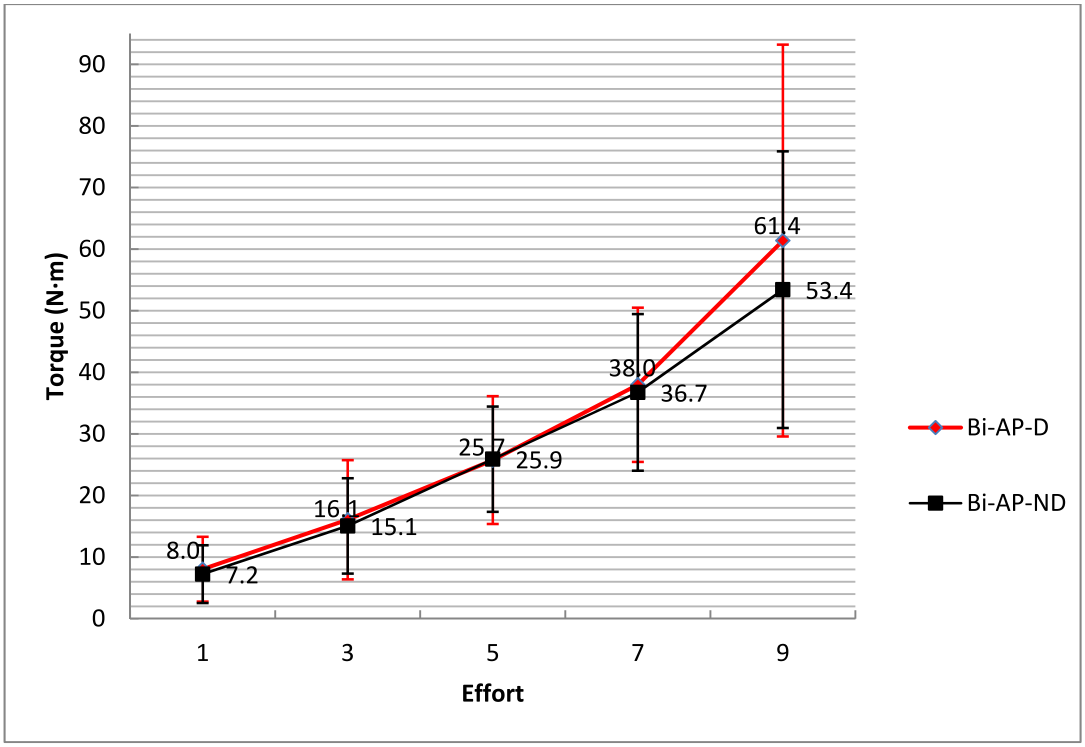

Figure 4.16. Elbow joint torque (mean ± SD) versus effort for the bilateral/anti-phase tasks. Bi-AP-D = Bilateral Anti-Phase Dominant; Bi-AP-ND = Bilateral Anti-Phase Non-Dominant; N·m = Newton·meters.

There was a significant main effect of task on peak joint torque ($F_{2,8} = 14.04$, $P < 0.0005$). Across all effort levels, subjects produced larger peak joint torques during unilateral task conditions than bilateral task conditions (in-phase and anti-phase) for the dominant and non-dominant arms. In addition, the main effect of effort level on peak joint torque was significant ($F_{4,6} = 60.94$, $P < 0.0001$). For each increase in effort level, the subjects produced significantly greater peak joint torques during the unilateral and bilateral (in-phase and anti-phase) task conditions for the dominant and non-dominant arms. However, unlike the angular displacement results, the main effect of arm on peak joint torque was not significant ($F_{1,9} = 1.44$, $P = 0.26$). While there was a strong trend for increased peak joint torques for the dominant arm as compared to the non-dominant arm for the unilateral task conditions, there were no differences in peak joint torque between the dominant and non-dominant arm for the bilateral task conditions.

There was one significant interaction effect across the main effects of task, arm, and effort level. The interaction between task and effort level was significant ($F_{8,2} = 2.20$, $P < 0.05$). Across all effort levels, larger peak joint torques were produced during the unilateral than the bilateral (in-phase and anti-phase) task conditions for the dominant and non-dominant arms. While there were no differences in peak joint torques between the bilateral/in-phase and bilateral/anti-phase task conditions for effort levels 1, 3, and 5, peak joint torque was greater for the bilateral/in-phase task conditions than the bilateral/anti-phase task conditions for effort levels 7 and 9. The interaction effects between task and arm across all effort levels ($F_{2,8} = 0.75$, $P = 0.49$), arm and effort level across all tasks ($F_{4,6} = 0.20$, $P = 0.94$), and task, arm, and effort level ($F_{8,2} = 0.24$, $P = 0.94$) were not significant.

CHAPTER 5

DISCUSSION

The purpose of this study was to investigate the biomechanics of movement-related effort associated with dynamic unilateral and bilateral single-joint movements. Data supported the hypotheses that there would be differences in the relationship between movement-related effort and biomechanical parameters as a function of task (unilateral vs. bilateral movements) and arm (dominant vs. non-dominant arms). More importantly, the methodology used in this study can be applied to evaluate changes in sense of effort during a wide variety of motor tasks.

5.1 Kinematic Considerations

Results indicated that during unilateral tasks, mean angular displacement (MAD), peak angular velocity (PAV), and peak angular acceleration (PAA) increased as effort levels increased from 1 through 9. Previous research (see Figure 5.1) reports increased kinematic quantities (MAD and PAA) as effort levels increased during unilateral arm movements (Moodie, 2007; Rosenbaum & Gregory, 2002).

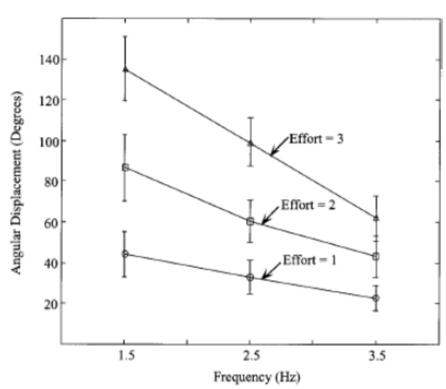

Figure 5.1. Relationship between angular displacement and prescribed effort for the three movement frequencies (Rosenbaum & Gregory, 2002)

Also, during unilateral tasks the results indicated decreased MAD in the non-dominant arm compared to the dominant arm. Again, previous research supports differences in kinematic characteristics between dominant and non-dominant arms. Whilst blinded to the specific condition, subjects produced reaching movements towards a target during loaded (2-kg mass) and unloaded conditions (Bagesteiro & Sainburg, 2003). For the non-dominant arm, there were no significant differences in final position accuracy between the loaded and unloaded conditions. In contrast, the dominant arm demonstrated a large and systematic overshoot of the final position during the loaded condition. Thus, the non-dominant arm produced effective load compensation, while the dominant arm overcompensated for the effects of load.

In an attempt to explain the above differences in limb control, Sainburg (2005) suggested different neural specializations within the brain for the dominant and non-dominant hemispheres. This motor control hypothesis, called dynamic dominance, proposes that control of the dominant arm involves more efficient and accurate coordination of INT forces. Thus, the dominant controller is specialized for feed-forward control of limb trajectory, while the non-dominant controller is specialized for feed-back control of limb position (see Figure 5.2). However, both hemispheres retain some level of trajectory and positional controllers.

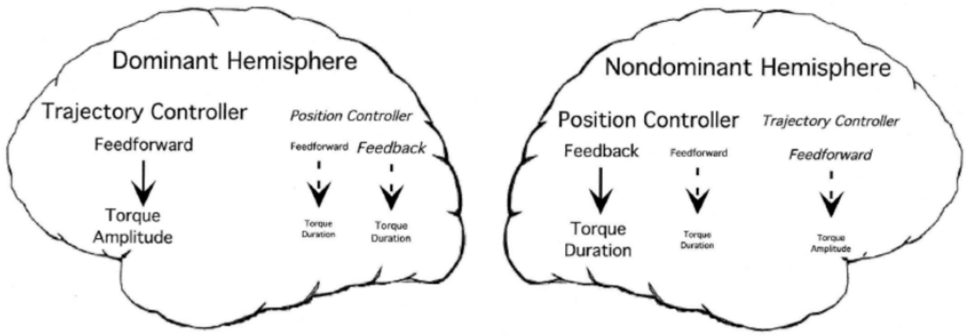

Figure 5.2. Specialized hemispheres for limb control (Sainburg, 2005)

The results indicated that during bilateral in-phase tasks, mean angular displacement (MAD), peak angular velocity (PAV), and peak angular acceleration (PAA) increased as effort levels increased from 1 through 9. Also, during bilateral in-phase tasks the findings revealed decreased MAD in the non-dominant arm compared to the dominant arm. Prior investigations corroborate disparities in kinematic quantities during bilateral in-phase movements. While performing an in-phase (symmetrical) circle-drawing task, subjects demonstrated a tilted-oval arm trajectory with the non-dominant arm compared with a more circular trajectory produced by the dominant arm; this difference in arm trajectory became more pronounced at higher movement speeds (Dounskaia, Nogueira, Swinnen, & Drummond, 2010).

The results showed that during bilateral anti-phase tasks, mean angular displacement (MAD), peak angular velocity (PAV), and peak angular acceleration (PAA) increased as effort levels increased from 1 through 9. Also, during bilateral anti-phase tasks the results demonstrated decreased MAD in the non-dominant arm compared to the dominant arm. Prior research substantiates that there are differences in kinematic quantities during bilateral anti-phase movements. While executing an anti-phase (asymmetrical) circle-drawing task, subjects exhibited a tilted-oval arm trajectory with the non-dominant arm compared with a more circular trajectory produced by the dominant arm; this difference in arm trajectory became more pronounced at higher movement speeds (Dounskaia et al., 2010). However, the differences in arm trajectory between the non-dominant and dominant limbs were more pronounced during anti-phase movements compared to in-phase movements.

5.2 Kinetic Considerations

By determining the relationship between peak joint torque (PJT) and effort (the slope of the function relating joint torque to sense of effort when torque is plotted against effort level), it is feasible to estimate deviations in sense of effort as a function of movement task condition. The results suggested a linear relationship between sense of effort and joint torque production during dynamic, unilateral and bilateral elbow movements (see Figure 4.13). This finding substantiates Andrews' (1983) hypothesis that force/torque are the biomechanical quantities most precisely associated with effort. Also, the result confirms previous biomechanical findings analyzing upper extremity movements.

During isometric elbow flexion movements of the right upper extremity (dominant limb except one subject), perceived effort, as measured using a 0-10 Numeric Rating Scale (NRS), increased with the intensity of the voluntary muscular contraction (Lampropoulou & Nowicky, 2011). Also, the perception of effort increased with normalized surface electromyography (sEMG) activity of the biceps brachii, brachialis, and brachioradialis. Dynamic movement of the upper limbs during a chest press exercise at varying effort levels (25%, 50%, 75%, and 100% MVC) showed that perceived effort increased with the level of force produced by muscular contraction (Jackson & Dishman, 2000). Additional research examining the effects of varying loads (light = 0 kg; medium 1.2 kg; heavy = 2.4 kg) on perceived effort during dynamic upper limb movements found that peak joint torque increased with effort and decreased with load (Moodie, 2007). Thus, previous research supports the results indicating significant increases in PJT as effort levels increased from 1 through 9.

During limb movements, there are resultant dynamic interactions between the joints of the moving limb, described as intersegmental interaction torque (INT) (Bagesteiro & Sainburg, 2002; Sainburg, 2005). The passive INT is required for coordination of movements involving multiple segments (Dounskaia, 2010). Other biomechanical quantities described as contributing to joint torque include net torque (NET) and muscular torque (MUS). Thus, the NET joint torque represents the summative values of INT and MUS, assuming a rigid body model (Bagesteiro & Sainburg, 2003).

Results suggested that during unilateral tasks, there is an increased sense of effort when using the non-dominant arm as compared to the dominant arm. Previous literature supports differences in biomechanical parameters between dominant and non-dominant limbs during dynamic movements. While performing a reaching task involving two joints (shoulder and elbow), the dominant arm motions produced approximately 50% less MUS as compared to the non-dominant limb (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). The non-dominant limb demonstrated larger MUS influences to NET, and thereby, less efficient movements (Sainburg, 2005). Also, the chosen pathway when reaching for a target varies between the dominant and non-dominant arms. The dominant arm moves in a gently curved medial to lateral direction, while the non-dominant path is largely straight (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000).

This difference in reaching paths influences shoulder and elbow kinematics, along with limb kinetics. Biomechanical analysis of the dominant limb revealed greater shoulder flexion elbow, producing considerable elbow INT. For the dominant limb, elbow MUS provided about 50% to elbow NET, while INT provided the other 50% (Bagesteiro & Sainburg, 2002; Sainburg & Kalakanis, 2000). Because of the straight line path taken by the non-dominant limb, there was minimal shoulder motion, and, as a result, almost the entire movement was generated by elbow MUS (Bagesteiro & Sainburg, 2002; Sainburg, 2005). This non-dominant force profile is thought to represent a less torque-efficient control strategy (Sainburg, 2005). Thus, a less efficient control strategy during non-dominant arm movements may be perceived as increased effort.

It has been suggested there only two steady states of human movement: in-phase and anti-phase. According to Turvey (1990), in-phase movements represent increased pattern stability compared to anti-phase movements. For example, when two persons were asked to perform in-phase or anti-phase movements with increasing frequency, each individual demonstrated a sudden transition from anti-phase coordination to in-phase, but not vice versa (Schmidt, Carello, & Turvey, 1990). Thus, based upon the assumption of an order parameter between two limbs, a model for understanding and quantifying human movement includes the dynamical systems approach to bimanual coordination. If the phase relation between two limbs represents an order parameter, then it must demonstrate specific characteristics such as modality, inaccessibility, sudden jumps, hysteresis, critical slowing down, and critical fluctuations (Turvey, 1990). Previous literature has confirmed these characteristics during human movements (Schoner, Haken, & Kelso, 1986; Schoner & Kelso, 1988).

A more recent model of bimanual movements proposes that there are two levels in the controller of the dominant and non-dominant arms: upper and lower levels (Dounskaia et al., 2010). The upper level of movement control encodes kinematic characteristics, while the lower level specifies muscular control or force. Bimanual interference between the two controllers occurs at the upper level due brain hemisphere cross-talk. However, at the lower level of the transformation of the kinematic plans into motor commands to the muscles of each arm, no inter-arm interference occurs. During in-phase (symmetrical) movements, a single kinematic plan can be produced in the dominant hemisphere; this single plan can be used for control of both arms. In contrast, during anti-phase (asymmetrical) movements, as two separate kinematic plans are needed for each limb, the non-dominant hemisphere becomes more involved creating interference (see Figure 5.3).

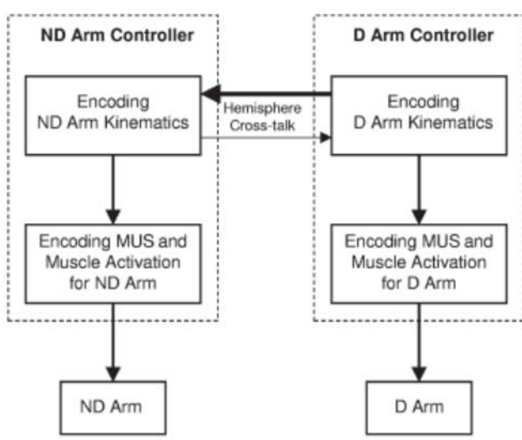

Figure 5.3. A model of control of bimanual movements (Dounskaia et al., 2010)

The results indicated that during bilateral tasks, there is a decreased sense of effort when performing in-phase as compared to anti-phase movements; prior research substantiates this finding. Absolute error (AE) and standard deviation (SD) values for a circle-drawing task demonstrated differences between in-phase (symmetrical) and anti-phase (asymmetrical) movements at slow (1.5 Hz) and fast (2.5) frequencies (Dounskaia et al., 2010). Coordination error and variability were higher during anti-phase tasks than in-phase tasks. During in-phase and anti-phase movements, the shoulder MUS index was reduced, while the elbow MUS index was larger in the non-dominant arm compared with the dominant arm. Control of intersegmental dynamics with INT was less efficient in the non-dominant compared to the dominant arm, more so during anti-phase movements. In other words, suppression of INT with MUS in the non-dominant arm was reliably deficient at the shoulder and excessive at the elbow. Thus, a less efficient control strategy during anti-phase movements, especially the non-dominant arm, may be perceived as increased effort.

The results suggested that sense of effort is increased during bilateral as compared to unilateral tasks. Previous findings indicated that the perception of effort in a bilateral isometric elbow task was significantly higher than in the unilateral condition (McLean et al., 2006). During bilateral movement, the perceived production of force was between 5.5 and 9.6% higher for a specified absolute force level (per arm). Mclean et al. (2006) concluded that the synchronized production of bilateral forces for a specified intensity challenges the motor control system. However, the specific mechanism (central and/or peripheral origin) of the inhibitory nature of this challenge remains unknown.

This study demonstrates a bilateral force deficit (BFD) during submaximal upper extremity movement tasks (see Figures 4.13 – 4.16). BFD has been demonstrated in both upper and lower extremities, both males and females, and in various levels of physical training (Archontides & Fazey, 1993; Bobbert et al., 2006; Kuruganti et al., 2011; McLean et al., 2006). Also, BFD exists in older populations (Hernandez et al., 2003; Owings & Grabiner, 1998). Bilateral force deficit is present at submaximal as well as maximal effort levels (Kuruganti et al., 2011; McLean et al., 2006). Previous studies have shown bilateral force deficit during isometric elbow flexion/extension tasks (Ohtsuki, 1983).

5.3 Summary

The following hypotheses were tested:

(1) Angular displacement will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

   a. Angular displacement will be greater for the dominant limb than non-dominant arm limb.

   b. Angular displacement will be greater for the unilateral than bilateral tasks.

   c. Angular displacement will be greater for the in-phase than anti-phase tasks.

(2) Peak angular velocity will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

a. Peak angular velocity will be greater for the dominant limb than non-dominant arm limb.

b. Peak angular velocity will be greater for the unilateral than bilateral tasks.

c. Peak angular velocity will be greater for the in-phase than anti-phase tasks.

(3) Peak angular acceleration will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase):

a. Peak angular acceleration will be greater for the dominant limb than non-dominant arm limb.

b. Peak angular acceleration will be greater for the unilateral than bilateral tasks.

c. Peak angular acceleration will be greater for the in-phase than anti-phase tasks.

(4) Peak joint torque will increase with effort and as a function of elbow joint task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase).

a. Peak joint torque will be greater for the dominant limb than non-dominant limb.

b. Peak joint torque will be greater for the unilateral than bilateral tasks.

c. Peak joint torque will be greater for the in-phase than anti-phase tasks.

5.3.1 Kinematics

Based upon the results of this experiment, hypotheses 1, 2 and 3 were accepted as MAD, PAV, PAA increased with effort and changed as a function of task. Quantitative values for MAD, PAV, and PAA decreased with the non-dominant arm compared to the dominant during the unilateral and bilateral tasks (in-phase and anti-phase). Quantitative values for MAD, PAV, and PAA decreased with the anti-phase task compared to the in-phase task. During unilateral tasks, there is an increased sense of effort when using the non-dominant arm due to strength and motor coordination differences. During bilateral tasks, there is a decreased sense of effort when performing in-phase movements due to increased pattern stability.

5.3.2 Kinetics

Based upon the results of this experiment, hypothesis 4 was accepted as PJT increased with effort and changed as a function of task. Quantitative values for PJT decreased with the non-dominant arm compared to the dominant during the unilateral and bilateral tasks (in-phase and anti-phase). Quantitative values for PJT decreased with the anti-phase task compared to the in-phase task. During unilateral tasks, sense of effort increased when using the non-dominant arm as compared to the dominant arm. While performing bilateral tasks, sense of effort decreased when performing in-phase movements as compared to anti-phase movements. Also, the sense of effort increased during bilateral tasks as compared to unilateral tasks.

5.4 Limitations

Several limitations should be considered when interpreting and applying these research findings to other situations. Subjects included young (20-40 years old), healthy males that may not represent the larger population. For example, two other variables that might affect the perception of effort during limb movements include gender and age. Also, the small sample size (n = 10) may influence interpretation of the statistical analyses and yield a *type-II* error.

Subjects generated upper-limb movements around the elbow joint. The elbow joint is classified as a hinge-joint and may not reflect the same biomechanical characteristics as other joints. Also, calculations for PJT values assumed a rigid-body model, but the markers for the motion capture may have shifted during limb movements due to skin turgor. Torque values were calculated only for the elbow, assuming a single-joint model of movement for the specified tasks. However, the shoulder and wrist joints remained relatively unfixed or mobile during the elbow tasks, perhaps allowing the generation of torques about other joints. For example, the leading joint hypothesis suggests that torque from adjacent joints (INT torque) is purposefully generated during upper-limb movements to produce coordinated movements (Dounskaia, 2010). The potential influence of INT torques, along with MUS and NET torques were not considered in the model of PJT calculations.

Lastly, subjects produced upper-limb movements at a single frequency of 2 Hz. This does not represent the only frequency at which the human body is capable of moving. Previous literature reports that movement frequency influences biomechanical parameters such as trajectory (Dounskaia et al., 2010).

5.5 Conclusions

The hypotheses were supported by differences between upper limb task (unilateral dominant, unilateral non-dominant, bilateral in-phase, bilateral anti-phase) and biomechanical parameters as a function of changing effort levels. Reviewing the graphical representations (Figures 4.1 to 4.16) for each of the biomechanical parameters (MAD, PAV, PAA, and PJT), the slope of the line for each variable increased as effort levels increased from 1 through 9. However, there was less distinction at the lower effort levels (i.e., minimal separation of the plots/lines representing different movement conditions at lower effort levels). Previous research supports the limited ability to gauge smaller or more complicated "fine-tuned" movements (Rosenbaum & Gregory, 2002). Although statistical significance was achieved for the higher effort levels, caution is advised when interpreting the results at lower effort levels.

Two factors may account for the lack of statistical significance at lower effort levels. First, standard deviation values were large, particularly at the higher effort levels. As compared to a small standard deviation value, a large standard deviation indicates more variability in the data set. Second, the sample size for this study was relatively small (n = 10). Generally, a larger sample provides a more reliable estimate of the standard deviation of the population than a smaller one. A small sample size also increases the likelihood of a *type-II* error. By increasing the sample size or power, there is likely less variability amongst the results, and a greater likelihood of rejecting the null hypothesis when it false avoiding a *type-II* error. With a small sample size (n = 10), the individual characteristics of each subject may dramatically affect the results.

For this study, subjects were all right-handed males, but absolute strength was highly variable. Because strength amongst subjects was highly variable, this created a wide range of strength values. Thus, torque values were normalized for individual subjects through strength testing with a dynamometer. Although strength testing normalizes joint torque values, kinematic data had large standard deviations perhaps influencing the statistical analyses.

Overall, the results indicated findings similar to previous research examining effort and biomechanical quantities during upper-limb movements (Jackson & Dishman, 2000; Lampropoulou & Nowicky, 2011; Moodie, 2007; Rosenbaum & Gregory, 2002), but also provide additional insight into the understanding of human movement. For example, with a predictable linear relationship between joint torque and effort during unilateral and bilateral movements, the slope of the line may be used during rehabilitation to assess whether or not a patient improved with corrective exercise. Thus, the findings contribute to the fundamental objective of quantifying and understanding human movement.

5.6 Future Directions

The study primarily focused on quantifying the effects of task and effort during upper-limb movements. However, the test subjects consisted exclusively of young, healthy males. The effects of age, gender, and pathology should be tested to determine their potential influences on upper-limb movements. For example, a thorough understanding of the influence of system perturbations such as stroke, Parkinson's, and ataxia on the movement system may allow successful clinical management and/or eradication of the disease. During stroke rehabilitation, an appreciation of the movement impairment may allow formulation of standardized clinical guidelines to improve the efficacy of upper limb rehabilitation regarding the recovery of bimanual coupling.

Potential effects of these characteristics on human movement may have applications in the realms of biomechanics, athletics, geriatrics, and physical medicine. For example, with predictable biomechanical values in relationship to effort for limb movements, a physician rehabilitating a stroke patient could use these established quantities as a clinical outcome measure. If there were established normative values for stroke patients, it would be feasible to ascertain the severity of the lesion, as well as determine progression during rehabilitation. After biomechanical testing of a specified movement or population, an established slope or statistical relationship may allow prediction of expected performance outcomes, eventually leading to the desired movement modifications and enhanced performance.

Specifically, by using an established torque-effort plot (see Figures 4.13 – 4.16) it should be possible to determine patient response to rehabilitation by referring to the slope of the function relating torque to effort. The slope of the torque-effort curve should get steeper with clinical improvement as the patient perceives less effort to move a limb segment. Thus, quantification of movement provides a reference or outcome measure (the slope of the function relating torque to effort), thereby benefiting clinicians, researchers, and patients.

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APPENDICES

Appendix A

CONSENT AND AUTHORIZATION FORM

BIOMECHANICS OF MOVEMENT-RELATED EFFORT

INTRODUCTION

The Department of Health, Sport and Exercise Sciences at the University of Kansas supports the practice of protection of human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and not participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY

The purpose of the study is to identify the biomechanical factors that contribute to movement-related sense of effort in upper-limb movements, such as movement speed (slow, medium, fast), load (light, medium, heavy), and body segment (movements performed with wrist, elbow, or shoulder joint; dominant and/or non-dominant arm). This information will then be used to develop diagnostic tools and rehabilitation protocols for clinical populations.

PROCEDURES

This study requires three visits that each last approximately one hour in duration; there will be a two-three day time period between successive study visits. During the first study visit, you will review this Consent and Authorization form. If you agree to participate in this study and sign this Consent and Authorization form, you will then complete a health history questionnaire to determine if you meet the study eligibility requirements. In order for you to be eligible, you must be between 18-40 years of age, right-arm dominant, and free from any past or current medical conditions, musculoskeletal injuries, or neurological disorders that may impair your ability to perform normal arm movements. If it is determined that you meet these eligibility requirements, you will be allowed to continue with the study and the maximal strength of the muscles that surround your elbow joints of your dominant and/or non-dominant arms will then be measured. In this experiment, you will produce very light-, light-, medium-, heavy-, and very heavy-effort movements with your upper extremities while seated in front of a table. In order to measure the movements of your elbow joint, a motion capture system will be used to track the positions of small, light emitting diodes (LEDs) placed on your forearms, and upper arms. The LEDs will be attached to your upper extremities via the use of surgical tape and elastic bandages. During the second study visit, you will be asked to move your forearm back and forth on top of the table in time with a metronome while holding different loads (light, medium, heavy) in your hand; these movements will be performed with your dominant arm. You will perform 30 trials in total; each trial will last approximately 20 seconds induration. During the third study visit, you will be asked to move your forearms back and forth on top of the table in time with a metronome while using your dominant arm, non-dominant arm, both arms together in-phase, and both arms together out-of-phase. You will perform 40 trials in total; each trial will last approximately 20 seconds in duration. Upon completion of this visit, your participation in the study will be concluded.

RISKS

Participants may experience a slight skin irritation due to the surgical tape and elastic bandages material used to attach the markers to the skin. Participants may also experience soreness in the muscles that surround the wrist, elbow, and shoulder joints due to the maximal strength testing and the joint flexion/extension movements performed in the study. In addition, due to the physiological stress involved in maximal strength testing may predispose participants to heart arrhythmias or other medical risks, e.g. heart attack, due to increased heart rate and blood pressure.

BENEFITS

There are no direct benefits to the subject. The indirect benefits of the study are that the information gained will be used to help individuals with movement disorders improve their functional capacity and regain the ability to perform activities of daily living.

PAYMENT TO PARTICIPANTS

Participants will not be compensated for their participation in the study.

INFORMATION TO BE COLLECTED

To perform this study, researchers will collect information about you. This information will be obtained from a health history taken by the researchers. Also, information will be collected from the study activities that are listed in the Procedures section of this Consent and Authorization form. Your name will not be associated in any way with the information collected about you or with the research findings from this study. The researchers will use a study number, initials, or a pseudonym instead of your name. The information collected about you will be used by Robert Gregory, Ph.D., members of the research team, KUCR and officials at KU that oversee research, including committees and offices that review and monitor research studies. The researchers will not share information about you with anyone not specified above unless required by law or unless you give written permission. Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for purposes of this study at any time in the future.

INSTITUTIONAL DISCLAIMER STATEMENT

In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION

You are not required to sign this consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING CONSENT AND AUTHORIZATION

You may withdraw your consent to participate in this study at any time. You also have the right to cancel your permission to use and disclose information collected about you at any time by contacting: Robert Gregory, Ph.D., University of Kansas, Health, Sport and Exercise Sciences, Robinson Center, 1301 Sunnyside Ave., Room 101A, Lawrence, KS 66045-7567, phone (785)864-0752, e-mail rwg@ku.edu. If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

PARTICIPANT CERTIFICATION

I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study and the use and disclosure of information about me for the study. I understand that if I have any additional questions about my rights as a research participant, I may call (785)864-7429 or write the Human Subjects Committee-Lawrence Campus (HSC-L), University of Kansas, 2385 Irving Hill Rd., Lawrence, KS 66045-7563, e-mail dhann@ku.edu. I agree to take part in this study as a research participant. I further agree to the uses and disclosures of my information as described above. By my signature I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

_________________________________ _______________________

Type/Print Participant's Name Date

____

Participant's Signature

<u>Appendix B</u>

Health History Questionnaire

Initials _______________

Gender _________ Age ________ Height ________________________ Weight ____________________

Upper arm length ____________ Forearm length _____________ Hand length _____________________

Please answer the following questions. Your name will not be associated in any way with the information collected about you or with the research findings from this study. The researchers will use a study number, initials, or a pseudonym instead of your name. The researchers will not share information about you with anyone unless required by law or unless you give written permission.

Do you have any past or current medical conditions (e.g., heart disease, diabetes, osteoporosis, etc.) that may prevent you from performing normal arm movements?

Yes *No*

Do you have any past or current musculoskeletal injuries (e.g., broken arm, dislocated shoulder, wrist sprain, etc.) that may prevent you from performing normal arm movements?

Yes *No*

Do you have any past or current neurological disorders (e.g., stroke, multiple sclerosis, epilepsy, etc.) that may prevent you from performing normal arm movements?

Yes *No*

If you answered "Yes" to any of the questions above, please explain the nature of the medical condition, musculoskeletal injury, or neurological disorder.

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Appendix C

Handedness Questionnaire

Please indicate below which hand you ordinarily use for each activity.

With which hand do you:

1. Draw?	1. Right	2. Either	3. Left
2. Write?	1. Right	2. Either	3. Left
3. Use a bottle opener?	1. Right	2. Either	3. Left
4. Throw a snowball to hit a tree?	1. Right	2. Either	3. Left
5. Use a hammer?	1. Right	2. Either	3. Left
6. Use a toothbrush?	1. Right	2. Either	3. Left
7. Use a screwdriver?	1. Right	2. Either	3. Left
8. Use an eraser on paper?	1. Right	2. Either	3. Left
9. Use a tennis racket?	1. Right	2. Either	3. Left
10. Use a pair of scissors?	1. Right	2. Either	3. Left
11. Hold a match when striking it?	1. Right	2. Either	3. Left
12. Stir a can of paint?	1. Right	2. Either	3. Left
13. On which shoulder do you rest a bat before swinging? or Remove the top card of a deck of cards (i.e., dealing)?	1. Right	2. Either	3. Left

Handedness
Right-handed → 13-17
Ambilateral → 18-32
Left-handed → 33-39

Reference

Chapman, L.J., & Chapman, J.P. (1987). The measurement of handedness. *Brain and Cognition, 6,* 175-183.

Appendix D

Strength Testing Results

Subject Number	**Flexion (N) Trial 1**	**Trial 2**	**Average (N·m)**	**Peak (N·m)**
1	187.67	183.33	53.8	54.4
2	206.33	207.33	66.2	66.3
3	154.00	153.33	47.6	47.7
4	178.06	181.33	57.5	58.0
5	140.33	138.67	39.1	39.3
6	270.67	268.67	78.2	78.5
7	260.67	253.67	69.4	70.4
8	149.00	153.00	42.3	42.8
9	165.67	158.33	42.1	43.1
10	190.00	194.33	61.5	62.2
Mean	**190.24**	**189.2**	**55.8**	**56.3**
St. Dev.	**44.66**	**43.5**	**13.1**	**13.1**

Subject Number	**Extension (N) Trial 1**	**Trial 2**	**Average (N·m)**	**Peak (N·m)**
1	126.5	144.0	39.2	41.8
2	184.0	183.0	58.7	58.9
3	132.5	116.0	38.5	41.1
4	129.0	134.5	42.2	43.0
5	105.0	102.0	29.0	29.4
6	204.0	170.0	54.2	59.2
7	194.0	158.5	47.6	52.4
8	114.0	122.0	33.0	34.2
9	123.0	127.0	32.5	33.0
10	146.0	160.0	49.0	51.2
Mean	**145.8**	**141.7**	**42.4**	**44.4**
St. Dev.	**35.27**	**25.87**	**9.8**	**10.6**

Appendix E

Flexion										
	Bi_AP-D-1					Bi_AP_D-3				
Subject	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
1	0.25	15.3	92.0	1310.4	7.8	0.24	38.6	229.0	4878.6	26.3
2	0.25	19.3	119.6	1770.3	15.0	0.26	31.4	179.9	2711.0	22.2
3	0.25	3.9	25.3	387.6	3.3	0.26	17.0	96.7	1473.0	9.5
4	0.25	20.5	130.2	1791.7	15.2	0.25	37.2	235.5	3440.2	27.8
5	0.24	3.2	22.3	377.1	2.7	0.25	13.9	93.3	1302.7	7.1
6	0.27	8.7	54.4	646.6	4.9	0.26	12.4	74.8	856.8	6.1
7	0.27	2.4	16.5	251.9	2.7	0.26	12.2	72.8	1315.1	9.1
8	0.25	13.5	88.9	1130.5	7.2	0.25	22.3	147.1	1898.1	11.4
9	0.26	10.1	71.9	973.3	5.7	0.26	21.0	122.0	1829.7	9.9
10	0.25	19.2	123.1	1826.1	16.9	0.25	37.4	229.8	3728.9	32.9
Extension										
	Bi_AP-D-1					Bi_AP_D-3				
Subject	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
1	0.25	15.3	96.8	1367.5	8.1	0.23	38.5	243.8	4304.4	23.3
2	0.24	19.2	126.8	1652.0	14.1	0.24	31.2	196.5	3039.0	24.7
3	0.26	4.0	27.1	366.9	3.2	0.24	16.5	106.2	1636.0	10.4
4	0.24	20.7	138.1	1831.0	15.5	0.25	37.5	228.8	3629.0	29.3
5	0.26	3.5	23.1	363.6	2.7	0.25	14.1	94.1	1132.3	6.3
6	0.28	8.8	52.3	677.0	5.1	0.27	12.4	71.8	967.8	6.8
7	0.23	2.1	14.6	276.1	2.8	0.24	12.1	78.0	1150.2	8.1
8	0.25	13.3	82.7	1308.8	8.2	0.25	21.9	145.8	1814.4	10.9
9	0.25	10.1	73.9	886.4	5.3	0.25	21.2	133.7	1876.7	10.1
10	0.25	18.5	119.1	1544.6	14.5	0.25	37.2	209.6	3274.1	29.0
Overall										
	Bi_AP-D-1					Bi_AP_D-3				
Subject	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque	Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)	(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
1	0.25	15.3	94.4	1339.0	7.9	0.24	38.6	236.4	4591.5	24.8
2	0.25	19.2	123.2	1711.2	14.5	0.25	31.3	188.2	2875.0	23.5
3	0.25	3.9	26.2	377.3	3.2	0.25	16.7	101.5	1554.5	10.0
4	0.25	20.6	134.2	1811.3	15.3	0.25	37.3	232.2	3534.6	28.5
5	0.25	3.4	22.7	370.4	2.7	0.25	14.0	93.7	1217.5	6.7
6	0.27	8.7	53.3	661.8	5.0	0.27	12.4	73.3	912.3	6.4
7	0.25	2.2	15.5	264.0	2.8	0.25	12.2	75.4	1232.7	8.6
8	0.25	13.4	85.8	1219.6	7.7	0.25	22.1	146.5	1856.2	11.1
9	0.25	10.1	72.9	929.9	5.5	0.25	21.1	127.8	1853.2	10.0
10	0.25	18.9	121.1	1685.3	15.7	0.25	37.3	219.7	3501.5	31.0
Avg.	**0.25**	**11.6**	**74.9**	**1037.0**	**8.0**	**0.25**	**24.3**	**149.5**	**2312.9**	**16.1**
St. Dev.	**0.01**	**6.9**	**44.2**	**598.9**	**5.3**	**0.01**	**10.8**	**65.0**	**1235.4**	**9.7**

Flexion										
Bi_AP_D-5						Bi_AP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	45.2	299.5	5040.0	27.1		0.24	50.9	309.3	7532.8	40.0
0.26	55.4	334.6	4280.4	34.3		0.26	73.1	446.0	6750.5	53.3
0.27	56.3	309.5	5452.9	32.2		0.23	76.9	490.2	8303.0	48.4
0.25	46.5	287.1	3983.8	32.0		0.25	56.3	362.9	4485.1	35.8
0.25	32.6	214.5	2651.0	13.5		0.26	68.2	434.6	5971.8	29.2
0.26	23.8	150.7	1651.2	10.7		0.25	37.8	250.5	2918.9	18.1
0.25	33.6	208.1	2750.1	17.8		0.26	68.5	428.5	5903.5	36.9
0.25	35.1	213.8	3087.7	17.8		0.25	45.5	279.4	4070.0	23.2
0.26	51.7	307.8	4517.4	23.0		0.26	70.1	402.6	5917.7	29.8
0.25	43.3	250.2	4692.2	41.0		0.24	62.1	391.3	5866.6	50.9
Extension										
Bi_AP_D-5						Bi_AP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	45.8	283.4	4342.5	23.5		0.23	51.1	319.4	5260.3	28.2
0.25	55.5	328.7	5795.3	45.9		0.24	73.4	475.7	8256.6	64.8
0.23	56.8	394.1	5603.4	33.0		0.26	76.9	435.2	7699.5	45.0
0.25	46.5	285.3	4609.4	36.8		0.26	56.1	319.4	5317.5	42.2
0.25	32.3	207.5	2598.9	13.2		0.24	68.0	417.8	7459.5	36.2
0.27	23.9	139.2	1999.1	12.8		0.26	37.5	227.4	3058.5	18.9
0.25	33.4	205.4	3185.0	20.4		0.24	68.2	435.8	7045.8	43.8
0.25	34.8	207.1	2962.8	17.1		0.25	45.6	269.2	4140.0	23.5
0.24	51.4	309.7	5061.5	25.6		0.24	69.9	421.1	7269.5	36.3
0.25	43.2	250.2	4237.8	37.2		0.25	62.0	361.1	6344.0	54.9
Overall										
Bi_AP_D-5						Bi_AP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	45.5	291.4	4691.2	25.3		0.23	51.0	314.4	6396.6	34.1
0.25	55.5	331.7	5037.9	40.1		0.25	73.3	460.8	7503.5	59.0
0.25	56.6	351.8	5528.2	32.6		0.25	76.9	462.7	8001.3	46.7
0.25	46.5	286.2	4296.6	34.4		0.25	56.2	341.1	4901.3	39.0
0.25	32.5	211.0	2625.0	13.4		0.25	68.1	426.2	6715.7	32.7
0.27	23.9	144.9	1825.2	11.7		0.25	37.7	238.9	2988.7	18.5
0.25	33.5	206.8	2967.6	19.1		0.25	68.4	432.1	6474.6	40.4
0.25	34.9	210.4	3025.3	17.5		0.25	45.5	274.3	4105.0	23.4
0.25	51.5	308.8	4789.5	24.3		0.25	70.0	411.9	6593.6	33.0
0.25	43.2	250.2	4465.0	39.1		0.25	62.1	376.2	6105.3	52.9
0.25	**42.4**	**259.3**	**3925.1**	**25.7**		**0.25**	**60.9**	**373.9**	**5978.6**	**38.0**
0.01	**10.8**	**65.5**	**1220.1**	**10.4**		**0.01**	**12.9**	**78.7**	**1541.5**	**12.5**

Flexion						Flexion				
Bi_AP_D-9						Bi_AP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.25	61.3	430.6	6713.6	35.7		0.26	12.9	84.1	1276.7	7.6
0.17	77.0	650.4	19829.1	153.7		0.24	17.4	117.4	1415.9	12.3
0.21	81.4	572.6	15444.0	89.2		0.25	3.6	22.8	366.7	3.2
0.26	67.7	440.1	6731.5	53.0		0.25	19.9	129.9	1679.3	14.3
0.20	79.1	632.0	16171.5	77.5		0.26	3.2	25.6	286.6	2.3
0.24	50.8	352.2	3783.2	23.1		0.26	10.3	63.7	773.4	5.6
0.22	82.4	635.4	10778.6	66.4		0.26	2.8	19.2	324.4	3.1
0.25	57.8	367.2	5466.9	30.8		0.25	10.2	68.0	757.4	5.2
0.26	89.2	499.7	8714.6	43.3		0.25	5.6	34.3	517.8	3.5
0.24	77.1	513.5	7153.6	61.7		0.25	16.3	102.7	1553.6	14.6
Extension										
Bi_AP_D-9						Bi_AP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	61.2	396.1	7361.6	39.1		0.24	12.7	88.8	1164.6	7.0
0.34	77.0	736.1	15068.9	117.1		0.27	17.5	109.1	1467.1	12.7
0.29	81.6	675.7	10990.2	63.8		0.25	3.6	23.2	323.9	2.9
0.24	67.9	460.4	7196.3	56.6		0.25	20.3	127.9	1787.3	15.1
0.32	79.3	687.5	13996.6	67.2		0.25	3.0	23.3	465.9	3.2
0.26	50.6	298.5	5000.6	30.2		0.28	10.2	57.4	795.5	5.8
0.28	82.6	638.5	12303.0	75.7		0.24	2.7	17.5	380.4	3.5
0.26	58.3	339.0	4898.1	27.7		0.25	10.0	67.0	979.4	6.4
0.24	89.4	547.6	9010.1	44.8		0.25	5.4	36.5	496.4	3.4
0.26	76.9	418.2	8300.9	71.3		0.25	16.6	96.8	1354.4	12.9
Overall										
Bi_AP_D-9						Bi_AP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	61.3	413.4	7037.6	37.4		0.25	12.8	86.5	1220.6	7.3
0.26	77.0	693.2	17449.0	135.4		0.25	17.4	113.3	1441.5	12.5
0.25	81.5	624.2	13217.1	76.5		0.25	3.6	23.0	345.3	3.1
0.25	67.8	450.3	6963.9	54.8		0.25	20.1	128.9	1733.3	14.7
0.26	79.2	659.7	15084.1	72.3		0.25	3.1	24.4	376.2	2.7
0.25	50.7	325.3	4391.9	26.7		0.27	10.3	60.5	784.4	5.7
0.25	82.5	637.0	11540.8	71.0		0.25	2.8	18.3	352.4	3.3
0.25	58.1	353.1	5182.5	29.2		0.25	10.1	67.5	868.4	5.8
0.25	89.3	523.7	8862.4	44.1		0.25	5.5	35.4	507.1	3.5
0.25	77.0	465.9	7727.2	66.5		0.25	16.4	99.7	1454.0	13.7
0.25	**72.4**	**514.6**	**9745.7**	**61.4**		**0.25**	**10.2**	**65.8**	**908.3**	**7.2**
0.01	**12.4**	**132.8**	**4378.3**	**31.8**		**0.01**	**6.4**	**40.2**	**521.4**	**4.7**

Flexion										
Bi_AP_ND-3						Bi_AP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	32.8	228.0	3784.7	20.6		0.23	41.1	285.2	5688.9	30.4
0.26	32.5	205.1	2687.9	22.1		0.26	53.2	304.6	4027.3	32.3
0.26	17.7	96.0	1873.6	11.8		0.23	50.6	330.3	4759.9	28.2
0.25	32.9	205.0	2692.2	22.1		0.25	41.7	270.8	3184.4	25.9
0.25	10.9	70.9	910.9	5.3		0.25	31.7	226.5	3422.9	17.1
0.27	16.1	97.5	1304.3	8.7		0.27	28.9	179.0	2273.8	14.4
0.25	11.4	83.0	980.7	7.1		0.25	33.0	204.4	2493.1	16.3
0.25	21.8	146.4	1741.0	10.5		0.25	34.9	215.8	3198.4	18.4
0.25	31.2	180.1	2921.3	15.2		0.26	55.3	327.6	5091.8	25.7
0.25	35.5	208.6	3425.4	30.3		0.25	42.6	234.7	5380.7	46.8
Extension										
Bi_AP_ND-3						Bi_AP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	32.8	221.3	3253.7	17.8		0.24	40.6	254.3	4325.7	23.4
0.25	32.4	205.1	2640.8	21.7		0.24	52.7	339.4	5551.4	44.0
0.24	17.5	106.3	1742.3	11.0		0.26	51.6	302.6	5145.7	30.4
0.25	32.9	211.1	2719.4	22.3		0.26	42.1	258.4	4055.1	32.5
0.26	10.7	64.7	1099.8	6.2		0.25	31.9	229.1	4621.9	22.8
0.27	16.3	92.8	1128.9	7.7		0.26	28.5	172.2	2176.4	13.8
0.25	11.0	79.3	1160.3	8.2		0.25	32.6	204.1	3148.6	20.2
0.26	21.9	143.5	1752.0	10.6		0.25	34.6	216.3	2840.8	16.5
0.25	31.3	186.6	2648.0	13.9		0.24	55.3	336.3	5344.7	27.0
0.25	35.8	208.6	3168.2	28.2		0.25	42.6	259.7	3585.0	31.7
Overall										
Bi_AP_ND-3						Bi_AP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	32.8	224.7	3519.2	19.2		0.23	40.9	269.7	5007.3	26.9
0.25	32.4	205.1	2664.4	21.9		0.25	52.9	322.0	4789.4	38.2
0.25	17.6	101.1	1807.9	11.4		0.25	51.1	316.4	4952.8	29.3
0.25	32.9	208.1	2705.8	22.2		0.25	41.9	264.6	3619.7	29.2
0.25	10.8	67.8	1005.3	5.7		0.25	31.8	227.8	4022.4	20.0
0.27	16.2	95.2	1216.6	8.2		0.27	28.7	175.6	2225.1	14.1
0.25	11.2	81.1	1070.5	7.6		0.25	32.8	204.3	2820.8	18.2
0.25	21.8	144.9	1746.5	10.5		0.25	34.8	216.1	3019.6	17.5
0.25	31.2	183.3	2784.7	14.5		0.25	55.3	332.0	5218.2	26.4
0.25	35.6	208.6	3296.8	29.2		0.25	42.6	247.2	4482.8	39.2
0.25	**24.3**	**152.0**	**2181.8**	**15.1**		**0.25**	**41.3**	**257.6**	**4015.8**	**25.9**
0.01	**9.8**	**60.9**	**929.9**	**7.7**		**0.01**	**9.4**	**53.4**	**1049.2**	**8.5**

Flexion										
Bi_AP_ND-7						Bi_AP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	45.0	321.4	5479.6	29.4		0.23	60.3	434.3	7605.5	40.4
0.25	69.6	417.4	6607.4	52.2		0.18	65.8	573.3	16080.6	124.9
0.26	65.4	378.2	7390.4	43.2		0.21	75.3	546.7	12598.7	72.9
0.24	55.1	333.6	5683.8	45.0		0.25	67.5	447.1	4914.4	39.1
0.25	66.7	418.5	6067.8	29.7		0.24	71.9	603.5	13074.4	62.8
0.25	41.6	265.7	3601.6	22.1		0.25	55.9	358.1	4538.5	27.5
0.26	67.7	432.6	5507.9	34.5		0.26	77.3	537.4	6647.9	41.4
0.25	39.2	242.3	3455.8	19.8		0.25	55.3	336.0	5348.0	30.1
0.26	69.7	407.9	6338.7	31.8		0.26	94.2	538.1	7854.9	39.2
0.25	61.3	352.2	7173.8	61.9		0.24	73.3	500.4	6871.9	59.3
Extension										
Bi_AP_ND-7						Bi_AP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	45.0	288.1	4814.8	25.9		0.24	60.1	409.1	7553.4	40.1
0.24	68.7	424.9	7887.6	62.0		0.33	65.8	577.8	11120.4	86.8
0.23	65.3	396.6	6179.6	36.3		0.21	75.3	546.7	12598.7	72.9
0.26	56.3	339.8	4817.0	38.4		0.26	67.4	380.7	6974.7	54.9
0.25	66.7	387.8	7604.9	36.9		0.25	71.9	590.8	11465.4	55.2
0.25	41.5	269.4	3156.9	19.5		0.24	56.3	359.6	5053.1	30.5
0.24	67.6	454.1	7653.3	47.5		0.25	77.3	541.7	9305.5	57.5
0.25	39.4	240.6	3392.7	19.5		0.24	54.9	334.0	5183.7	29.2
0.24	69.0	423.0	6347.5	31.8		0.24	94.3	582.7	9699.4	48.1
0.25	61.4	383.6	5479.7	47.6		0.26	73.4	479.2	8217.6	70.6
Overall										
Bi_AP_ND-7						Bi_AP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	45.0	304.7	5147.2	27.6		0.23	60.2	421.7	7579.5	40.2
0.25	69.1	421.2	7247.5	57.1		0.25	65.8	575.6	13600.5	105.9
0.25	65.3	387.4	6785.0	39.8		0.25	75.3	568.2	11264.9	65.3
0.25	55.7	336.7	5250.4	41.7		0.25	67.5	413.9	5944.6	47.0
0.25	66.7	403.2	6836.3	33.3		0.24	71.9	597.2	12269.9	59.0
0.25	41.5	267.5	3379.2	20.8		0.25	56.1	358.9	4795.8	29.0
0.25	67.6	443.4	6580.6	41.0		0.25	77.3	539.6	7976.7	49.5
0.25	39.3	241.5	3424.2	19.7		0.25	55.1	335.0	5265.8	29.7
0.25	69.3	415.4	6343.1	31.8		0.25	94.2	560.4	8777.2	43.6
0.25	61.3	367.9	6326.8	54.7		0.25	73.3	489.8	7544.7	65.0
0.25	**58.1**	**358.9**	**5732.0**	**36.7**		**0.25**	**69.7**	**486.0**	**8502.0**	**53.4**
0.01	**11.9**	**68.8**	**1394.7**	**12.7**		**0.01**	**11.6**	**96.5**	**2994.3**	**22.5**

Flexion										
Bi_IP-D-1						Bi_IP_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	21.4	142.5	1920.3	11.0		0.24	38.7	267.8	4557.2	24.6
0.26	23.2	135.3	2444.3	20.2		0.26	38.8	226.8	3921.6	31.5
0.25	4.2	27.6	477.7	3.8		0.26	20.2	116.4	1990.4	12.4
0.25	20.1	129.1	1577.3	13.5		0.25	32.5	201.3	2649.8	21.8
0.25	4.3	27.5	429.0	3.0		0.26	9.8	64.8	751.1	4.5
0.25	6.9	46.5	500.3	4.1		0.25	13.7	86.4	1006.8	7.0
0.25	4.2	33.3	337.1	3.2		0.24	15.7	108.8	1325.5	9.2
0.25	16.2	104.3	1164.2	7.4		0.25	23.2	139.7	1976.3	11.8
0.25	8.4	50.0	1078.9	6.2		0.25	13.4	92.8	1145.7	6.6
0.25	19.0	121.9	1881.0	17.3		0.25	35.1	223.5	3221.3	28.6
Extension										
Bi_IP-D-1						Bi_IP_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	21.4	146.2	1917.3	10.9		0.23	38.9	253.7	3946.7	21.4
0.25	23.0	135.5	1898.2	16.0		0.25	38.7	235.5	3341.8	27.1
0.25	4.3	28.2	379.9	3.3		0.24	20.2	131.8	1693.9	10.7
0.25	20.1	127.3	2031.2	17.0		0.25	32.7	197.9	3132.8	25.5
0.25	4.4	28.6	395.9	2.8		0.25	9.4	61.3	820.5	4.8
0.25	6.9	45.0	631.5	4.8		0.25	13.9	97.1	1396.6	9.3
0.25	4.2	32.0	640.3	5.0		0.26	16.4	107.1	1383.7	9.5
0.25	16.2	102.3	1472.8	9.0		0.25	23.1	142.0	2104.6	12.5
0.25	8.7	51.5	834.7	5.1		0.25	13.7	96.7	1107.6	6.4
0.25	19.0	123.8	1569.0	14.7		0.25	35.3	204.6	2993.2	26.7
Overall										
Bi_IP-D-1						Bi_IP_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	21.4	144.4	1918.8	10.9		0.23	38.8	260.8	4251.9	23.0
0.25	23.1	135.4	2171.2	18.1		0.25	38.7	231.1	3631.7	29.3
0.25	4.3	27.9	428.8	3.5		0.25	20.2	124.1	1842.2	11.6
0.25	20.1	128.2	1804.3	15.3		0.25	32.6	199.6	2891.3	23.6
0.25	4.4	28.1	412.5	2.9		0.25	9.6	63.0	785.8	4.7
0.25	6.9	45.7	565.9	4.4		0.25	13.8	91.8	1201.7	8.1
0.25	4.2	32.7	488.7	4.1		0.25	16.1	107.9	1354.6	9.4
0.25	16.2	103.3	1318.5	8.2		0.25	23.2	140.9	2040.4	12.1
0.25	8.5	50.8	956.8	5.6		0.25	13.6	94.7	1126.6	6.5
0.25	19.0	122.8	1725.0	16.0		0.25	35.2	214.1	3107.3	27.6
0.25	**12.8**	**81.9**	**1179.0**	**8.9**		**0.25**	**24.2**	**152.8**	**2223.4**	**15.6**
0.00	**7.8**	**48.9**	**690.6**	**5.8**		**0.01**	**11.2**	**68.2**	**1181.9**	**9.3**

Flexion										
Bi_IP_D-5						Bi_IP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	48.4	296.4	6570.6	35.0		0.24	63.0	465.0	8224.2	43.6
0.26	64.0	377.1	7312.8	57.6		0.26	87.0	489.0	7875.6	61.9
0.27	56.6	307.2	5676.5	33.5		0.27	81.7	435.6	9197.0	53.5
0.25	47.3	299.0	3695.2	29.8		0.25	66.1	404.6	6157.5	48.6
0.25	34.5	225.0	3115.4	15.7		0.26	70.5	420.2	7496.4	36.4
0.25	23.5	175.9	1937.0	12.4		0.25	43.2	296.8	3206.8	19.8
0.25	37.3	232.4	2901.0	18.7		0.26	71.7	438.6	5116.8	32.1
0.25	42.1	258.8	3512.3	20.1		0.25	47.0	272.9	4311.9	24.5
0.25	55.1	332.6	4667.4	23.7		0.25	70.2	420.7	6084.5	30.6
0.25	45.1	265.3	4275.7	37.5		0.25	62.1	363.3	6463.2	55.9
Extension										
Bi_IP_D-5						Bi_IP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	47.9	294.8	4781.1	25.7		0.24	62.0	478.6	5823.3	31.1
0.24	64.1	389.9	5280.5	42.0		0.24	87.0	533.8	10009.8	78.3
0.23	56.6	375.1	5221.4	30.9		0.23	81.3	502.3	9066.3	52.8
0.25	47.5	297.0	4536.2	36.2		0.25	66.3	382.2	6305.2	49.8
0.25	33.7	212.5	2935.4	14.8		0.24	70.5	507.4	9448.2	45.7
0.25	23.5	146.3	2245.2	14.2		0.26	43.2	273.2	4056.1	24.7
0.24	36.8	230.6	3443.4	22.0		0.24	71.1	454.3	7879.4	48.9
0.25	42.0	246.3	3890.6	22.2		0.25	46.9	278.8	4241.3	24.1
0.25	55.6	337.7	5466.0	27.6		0.25	69.8	412.8	7426.4	37.1
0.25	44.7	257.1	4016.8	35.3		0.24	62.8	391.3	4962.4	43.3
Overall										
Bi_IP_D-5						Bi_IP_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	48.2	295.6	5675.8	30.4		0.24	62.5	471.8	7023.8	37.3
0.25	64.0	383.5	6296.6	49.8		0.25	87.0	511.4	8942.7	70.1
0.25	56.6	341.2	5449.0	32.2		0.25	81.5	469.0	9131.7	53.2
0.25	47.4	298.0	4115.7	33.0		0.25	66.2	393.4	6231.3	49.2
0.25	34.1	218.7	3025.4	15.3		0.25	70.5	463.8	8472.3	41.0
0.25	23.5	161.1	2091.1	13.3		0.25	43.2	285.0	3631.5	22.2
0.25	37.1	231.5	3172.2	20.4		0.25	71.4	446.4	6498.1	40.5
0.25	42.1	252.6	3701.4	21.2		0.25	46.9	275.9	4276.6	24.3
0.25	55.4	335.2	5066.7	25.6		0.25	70.0	416.7	6755.5	33.8
0.25	44.9	261.2	4146.2	36.4		0.25	62.5	377.3	5712.8	49.6
0.25	**45.3**	**277.8**	**4274.0**	**27.7**		**0.25**	**66.2**	**411.1**	**6667.6**	**42.1**
0.01	**11.9**	**66.1**	**1332.2**	**11.0**		**0.00**	**13.6**	**79.4**	**1847.1**	**14.2**

Flexion										
Bi_IP_D-9						Bi_IP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	70.0	441.6	8532.9	45.2		0.25	18.6	110.6	2010.3	11.4
0.21	93.9	710.1	13503.0	105.1		0.25	23.2	142.9	2350.1	19.5
0.21	89.7	633.2	13861.0	80.1		0.24	4.7	31.8	431.0	3.5
0.25	72.5	522.6	8054.7	63.2		0.25	15.1	96.2	1525.5	13.1
0.28	82.9	551.8	9723.2	47.0		0.24	4.5	30.9	430.0	3.0
0.24	58.6	407.2	4842.7	29.3		0.25	7.9	51.8	642.6	4.9
0.27	93.7	578.5	9876.4	61.0		0.25	3.5	23.7	330.4	3.2
0.25	66.5	402.6	6392.7	35.8		0.26	16.3	101.3	1199.7	7.6
0.26	83.4	455.3	7845.3	39.1		0.25	9.2	58.5	779.8	4.8
0.26	81.7	526.6	7051.0	60.8		0.24	20.5	129.8	1792.3	16.6
Extension										
Bi_IP_D-9						Bi_IP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	69.9	419.6	7293.4	38.7		0.24	18.9	115.0	1692.8	9.8
0.29	93.9	717.7	12176.9	94.9		0.25	22.8	145.6	1906.3	16.0
0.29	89.8	667.1	11504.5	66.7		0.25	4.8	30.7	439.2	3.6
0.25	72.4	512.9	7924.2	62.2		0.26	14.7	94.5	1172.5	10.4
0.23	83.3	572.7	11121.1	53.6		0.26	4.6	28.6	437.2	3.0
0.24	57.9	372.9	6235.7	37.4		0.25	7.8	49.8	770.9	5.6
0.23	93.7	614.8	9356.0	57.8		0.25	3.5	22.5	335.0	3.2
0.24	66.7	391.7	6686.3	37.4		0.25	16.1	102.6	1524.7	9.3
0.24	83.0	501.4	8997.6	44.7		0.25	9.5	60.3	819.4	5.0
0.24	81.7	511.2	8667.7	74.4		0.25	19.8	123.3	1981.4	18.2
Overall										
Bi_IP_D-9						Bi_IP_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	69.9	430.6	7913.2	41.9		0.25	18.7	112.8	1851.6	10.6
0.25	93.9	713.9	12840.0	100.0		0.25	23.0	144.2	2128.2	17.8
0.25	89.7	650.2	12682.7	73.4		0.25	4.7	31.2	435.1	3.6
0.25	72.4	517.8	7989.4	62.7		0.25	14.9	95.4	1349.0	11.8
0.25	83.1	562.3	10422.2	50.3		0.25	4.6	29.7	433.6	3.0
0.24	58.3	390.0	5539.2	33.3		0.25	7.9	50.8	706.8	5.3
0.25	93.7	596.7	9616.2	59.4		0.25	3.5	23.1	332.7	3.2
0.25	66.6	397.1	6539.5	36.6		0.25	16.2	101.9	1362.2	8.4
0.25	83.2	478.4	8421.5	41.9		0.25	9.3	59.4	799.6	4.9
0.25	81.7	518.9	7859.4	67.6		0.25	20.1	126.6	1886.8	17.4
0.25	**79.2**	**525.6**	**8982.3**	**56.7**		**0.25**	**12.3**	**77.5**	**1128.6**	**8.6**
0.01	**12.0**	**107.3**	**2417.0**	**20.4**		**0.00**	**7.2**	**44.0**	**673.6**	**5.6**

Flexion										
Bi_IP_ND-3						Bi_IP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	39.3	276.0	3938.0	21.4		0.26	55.4	340.1	5870.0	31.4
0.25	34.8	211.3	3087.9	25.1		0.27	62.9	350.8	4958.3	39.5
0.27	20.9	121.1	1952.5	12.2		0.27	60.9	346.5	6153.7	36.2
0.25	31.3	201.3	2735.6	22.4		0.25	47.8	293.9	4243.3	34.0
0.25	9.5	62.7	797.1	4.7		0.26	33.3	200.1	2957.1	14.9
0.25	15.3	98.0	1230.3	8.3		0.25	27.4	176.4	2355.0	14.8
0.26	14.7	101.0	1323.1	9.2		0.25	33.5	206.9	2508.4	16.4
0.25	25.8	169.3	2375.2	13.9		0.26	39.7	242.2	3208.9	18.5
0.25	15.1	92.5	1436.2	8.0		0.25	35.8	208.9	3225.6	16.7
0.26	34.2	197.2	4007.7	35.2		0.25	45.2	268.4	4444.0	38.9
Extension										
Bi_IP_ND-3						Bi_IP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	39.6	271.8	4168.2	22.6		0.23	54.7	363.2	5466.6	29.3
0.24	34.5	223.5	2816.7	23.0		0.24	62.9	402.0	6739.5	53.2
0.23	20.8	145.0	1761.8	11.1		0.24	60.8	371.2	5981.5	35.2
0.25	31.0	197.1	2696.4	22.1		0.25	47.7	300.2	4596.3	36.7
0.24	9.1	59.4	880.1	5.1		0.24	33.1	214.9	2949.4	14.9
0.25	15.4	107.1	1313.8	8.8		0.25	27.7	169.6	2467.6	15.5
0.24	14.6	107.8	1383.0	9.5		0.25	33.5	210.9	3248.9	20.8
0.26	25.9	161.9	2010.9	12.0		0.26	39.5	227.1	3138.1	18.1
0.25	15.3	99.9	1188.3	6.8		0.25	36.1	215.9	3157.1	16.3
0.25	34.8	216.7	2770.3	24.8		0.25	45.0	247.9	4617.5	40.4
Overall										
Bi_IP_ND-3						Bi_IP_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	39.5	273.9	4053.1	22.0		0.24	55.0	351.7	5668.3	30.3
0.25	34.7	217.4	2952.3	24.1		0.25	62.9	376.4	5848.9	46.3
0.25	20.8	133.1	1857.1	11.7		0.25	60.8	358.9	6067.6	35.7
0.25	31.2	199.2	2716.0	22.3		0.25	47.7	297.0	4419.8	35.3
0.25	9.3	61.1	838.6	4.9		0.25	33.2	207.5	2953.3	14.9
0.25	15.4	102.5	1272.0	8.5		0.25	27.6	173.0	2411.3	15.2
0.25	14.6	104.4	1353.0	9.4		0.25	33.5	208.9	2878.7	18.6
0.25	25.8	165.6	2193.0	13.0		0.26	39.6	234.7	3173.5	18.3
0.25	15.2	96.2	1312.3	7.4		0.25	36.0	212.4	3191.4	16.5
0.25	34.5	207.0	3389.0	30.0		0.25	45.1	258.2	4530.8	39.6
0.25	**24.1**	**156.0**	**2193.7**	**15.3**		**0.25**	**44.1**	**267.9**	**4114.3**	**27.1**
0.01	**10.5**	**67.4**	**1055.0**	**8.5**		**0.00**	**12.3**	**73.3**	**1375.1**	**11.7**

Flexion										
Bi_IP_ND-7						Bi_IP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.26	57.9	381.8	6378.0	34.0		0.22	65.6	516.5	9785.9	51.6
0.25	80.2	506.9	7896.5	62.1		0.21	79.8	611.6	14461.8	112.5
0.27	80.8	429.8	9666.7	56.2		0.22	86.0	571.1	13004.3	75.2
0.25	60.3	354.8	6371.9	50.3		0.25	68.8	427.4	5894.7	46.6
0.27	70.7	406.7	7464.1	36.3		0.19	83.0	635.3	17271.8	82.7
0.24	48.2	324.6	3705.2	22.7		0.24	57.7	387.6	5307.7	32.0
0.26	69.2	429.7	5879.7	36.8		0.25	93.7	599.9	11964.2	73.6
0.26	46.8	277.7	4495.2	25.5		0.25	66.0	396.4	6266.8	35.1
0.26	72.3	440.4	6437.2	32.3		0.26	80.5	482.4	6908.9	34.6
0.25	64.2	390.0	6928.1	59.8		0.25	79.2	475.8	8085.3	69.5

Extension										
Bi_IP_ND-7						Bi_IP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	57.5	383.3	6484.0	34.6		0.24	65.8	505.4	9486.9	50.1
0.24	79.8	478.5	7522.7	59.2		0.30	79.8	659.8	12304.7	95.9
0.23	80.3	508.6	8057.2	47.0		0.28	86.0	658.4	10442.0	60.6
0.25	61.6	392.8	4902.5	39.0		0.25	69.6	412.3	6638.6	52.3
0.23	70.5	481.2	8684.8	42.0		0.31	83.1	734.5	14632.5	70.2
0.26	48.4	296.9	4030.2	24.6		0.24	56.8	373.1	5567.3	33.5
0.24	69.1	435.7	7401.3	46.0		0.25	93.5	635.5	8772.5	54.3
0.25	46.9	286.0	3794.1	21.7		0.25	65.8	372.5	6571.2	36.8
0.24	71.8	433.0	7380.6	36.9		0.24	80.5	533.8	8328.3	41.5
0.25	63.3	376.0	6382.0	55.2		0.25	77.8	477.6	7359.2	63.4

Overall										
Bi_IP_ND-7						Bi_IP_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	57.7	382.5	6431.0	34.3		0.23	65.7	511.0	9636.4	50.9
0.25	80.0	492.7	7709.6	60.6		0.25	79.8	635.7	13383.3	104.2
0.25	80.6	469.2	8862.0	51.6		0.25	86.0	614.8	11723.2	67.9
0.25	60.9	373.8	5637.2	44.7		0.25	69.2	419.8	6266.6	49.5
0.25	70.6	444.0	8074.4	39.2		0.25	83.0	684.9	15952.2	76.4
0.25	48.3	310.7	3867.7	23.6		0.24	57.3	380.4	5437.5	32.7
0.25	69.2	432.7	6640.5	41.4		0.25	93.6	617.7	10368.4	63.9
0.25	46.9	281.9	4144.7	23.6		0.25	65.9	384.5	6419.0	35.9
0.25	72.0	436.7	6908.9	34.6		0.25	80.5	508.1	7618.6	38.0
0.25	63.7	383.0	6655.0	57.5		0.25	78.5	476.7	7722.3	66.5
0.25	**65.0**	**400.7**	**6493.1**	**41.1**		**0.25**	**75.9**	**523.3**	**9452.7**	**58.6**
0.00	**11.8**	**67.4**	**1597.1**	**12.8**		**0.01**	**11.1**	**110.0**	**3424.6**	**21.9**

Flexion										
Uni_D-1						Uni_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	22.1	147.7	2300.9	12.9		0.23	41.4	268.2	5915.6	31.6
0.25	25.4	157.1	2140.8	17.8		0.25	40.8	241.3	4275.5	34.2
0.25	5.5	36.6	530.9	4.1		0.26	24.1	146.4	2340.7	14.4
0.25	21.5	135.3	1792.9	15.2		0.25	38.6	235.7	3464.2	28.0
0.25	5.9	40.2	616.9	3.9		0.24	16.4	111.6	1730.6	9.1
0.25	6.7	42.9	533.2	4.2		0.25	16.0	105.2	1257.2	8.5
0.25	6.5	40.4	702.8	5.4		0.25	17.8	122.2	1526.7	10.4
0.26	18.9	117.7	1612.9	9.8		0.25	27.0	163.8	2592.6	15.1
0.25	11.9	72.8	1370.6	7.7		0.26	41.2	253.4	3310.4	17.1
0.25	21.0	126.4	1732.7	16.1		0.25	42.9	259.4	4557.1	39.8
Extension										
Uni_D-1						Uni_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	22.0	145.6	2374.7	13.3		0.23	41.0	259.5	4456.5	24.1
0.25	25.4	163.1	2145.7	17.9		0.25	40.9	247.2	3509.0	28.4
0.25	5.5	36.2	480.4	3.8		0.24	24.0	149.8	2780.2	16.9
0.25	21.7	138.6	1975.3	16.6		0.25	38.5	240.3	3340.7	27.0
0.26	5.9	37.8	562.8	3.6		0.26	16.8	111.3	1262.6	6.9
0.25	6.8	41.1	666.5	5.0		0.26	16.1	100.5	1399.5	9.3
0.26	6.8	42.5	561.1	4.6		0.25	17.6	114.4	1626.4	11.0
0.25	18.8	122.8	1605.4	9.8		0.25	26.4	164.2	2233.2	13.2
0.25	12.2	73.5	978.3	5.8		0.24	41.3	265.5	3714.6	19.0
0.25	20.6	127.9	2024.6	18.5		0.25	42.9	264.8	3576.0	31.6
Overall										
Uni_D-1						Uni_D-3				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	22.1	146.7	2337.8	13.1		0.23	41.2	263.9	5186.1	27.8
0.25	25.4	160.1	2143.3	17.9		0.25	40.8	244.3	3892.2	31.3
0.25	5.5	36.4	505.7	4.0		0.25	24.1	148.1	2560.5	15.7
0.25	21.6	136.9	1884.1	15.9		0.25	38.6	238.0	3402.5	27.5
0.25	5.9	39.0	589.8	3.7		0.25	16.6	111.4	1496.6	8.0
0.25	6.7	42.0	599.8	4.6		0.25	16.0	102.8	1328.3	8.9
0.25	6.6	41.4	632.0	5.0		0.25	17.7	118.3	1576.5	10.7
0.25	18.9	120.3	1609.1	9.8		0.25	26.7	164.0	2412.9	14.2
0.25	12.1	73.2	1174.4	6.7		0.25	41.2	259.5	3512.5	18.1
0.25	20.8	127.2	1878.6	17.3		0.25	42.9	262.1	4066.6	35.7
0.25	**14.6**	**92.3**	**1335.5**	**9.8**		**0.25**	**30.6**	**191.2**	**2943.5**	**19.8**
0.01	**8.0**	**50.5**	**717.6**	**5.8**		**0.01**	**11.4**	**68.4**	**1279.1**	**10.0**

Flexion										
Uni_D-5						Uni_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.25	58.2	351.4	6628.8	35.3		0.22	73.7	509.6	12197.7	64.1
0.25	70.5	409.2	7126.6	56.1		0.25	92.2	617.8	8075.0	63.4
0.27	71.7	383.1	8157.0	47.6		0.27	86.7	475.8	8580.2	50.0
0.25	54.0	351.3	4212.9	33.7		0.25	69.7	413.5	7638.0	60.0
0.26	45.6	259.5	4352.2	21.5		0.24	75.8	477.9	8892.8	43.0
0.25	24.9	162.1	1861.0	12.0		0.25	42.6	276.7	3070.6	19.0
0.25	53.3	312.9	4548.1	28.7		0.26	87.0	528.7	7226.6	44.9
0.26	45.4	265.9	3535.6	20.3		0.25	57.7	339.7	5162.9	29.1
0.26	63.3	374.1	5040.8	25.5		0.26	85.9	500.3	7353.2	36.7
0.25	52.5	322.9	4718.6	41.2		0.25	74.3	450.0	6062.9	52.5
Extension										
Uni_D-5						Uni_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	58.2	332.2	5459.9	29.3		0.23	74.7	460.4	9429.1	49.8
0.25	71.2	400.9	6622.6	52.3		0.25	92.2	601.2	10429.0	81.5
0.23	72.2	466.1	6931.7	40.6		0.23	86.2	550.8	9163.0	53.3
0.25	53.7	330.5	5591.3	44.3		0.25	70.6	418.7	6376.7	50.3
0.23	45.0	295.1	4432.9	21.9		0.27	75.1	420.7	6446.2	31.5
0.25	24.8	152.2	2164.8	13.7		0.25	42.1	256.7	3844.4	23.5
0.25	52.7	318.2	5345.0	33.5		0.24	86.6	538.0	9500.8	58.7
0.26	45.0	245.8	4118.3	23.4		0.25	57.5	329.2	5734.6	32.2
0.24	63.0	394.3	6168.9	31.0		0.24	85.8	550.9	9212.8	45.8
0.25	52.5	300.4	4990.7	43.5		0.25	74.4	429.9	7904.0	68.0
Overall										
Uni_D-5						Uni_D-7				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.25	58.2	341.8	6044.3	32.3		0.22	74.2	485.0	10813.4	56.9
0.25	70.8	405.0	6874.6	54.2		0.25	92.2	609.5	9252.0	72.5
0.25	71.9	424.6	7544.4	44.1		0.25	86.5	513.3	8871.6	51.7
0.25	53.8	340.9	4902.1	39.0		0.25	70.2	416.1	7007.3	55.2
0.25	45.3	277.3	4392.5	21.7		0.25	75.4	449.3	7669.5	37.2
0.25	24.9	157.1	2012.9	12.8		0.25	42.3	266.7	3457.5	21.2
0.25	53.0	315.5	4946.5	31.1		0.25	86.8	533.4	8363.7	51.8
0.26	45.2	255.8	3826.9	21.8		0.25	57.6	334.4	5448.8	30.7
0.25	63.2	384.2	5604.8	28.2		0.25	85.9	525.6	8283.0	41.2
0.25	52.5	311.6	4854.7	42.3		0.25	74.4	439.9	6983.5	60.3
0.25	**53.9**	**321.4**	**5100.4**	**32.8**		**0.25**	**74.5**	**457.3**	**7615.0**	**47.9**
0.00	**13.8**	**78.7**	**1565.1**	**12.4**		**0.01**	**15.2**	**100.5**	**2061.4**	**15.2**

Flexion										
Uni_D-9						Uni_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	89.3	592.1	10542.0	55.5		0.25	25.1	158.5	2474.8	13.8
0.22	99.0	714.6	12181.7	95.0		0.25	23.4	138.1	1895.4	16.0
0.26	94.0	536.1	10107.1	58.7		0.26	5.3	31.9	522.0	4.1
0.24	84.1	537.9	8866.1	69.4		0.24	21.2	143.8	1753.3	14.9
0.27	94.7	643.1	13855.3	66.5		0.25	4.4	31.6	413.9	2.9
0.25	62.8	448.5	5846.4	35.1		0.25	10.5	74.9	973.5	6.8
0.26	109.4	759.1	12918.8	79.4		0.25	6.3	42.8	504.6	4.2
0.26	68.4	405.6	6790.5	37.9		0.25	18.1	114.2	1431.3	8.8
0.26	100.1	585.5	9151.3	45.5		0.25	9.3	64.1	846.5	5.1
0.25	88.8	579.2	10238.3	87.7		0.25	20.7	119.1	2680.6	24.1
Extension										
Uni_D-9						Uni_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	90.2	557.3	10574.4	55.7		0.23	25.1	163.4	2488.8	13.9
0.28	99.0	703.9	12276.2	95.7		0.25	23.1	144.0	1846.5	15.6
0.23	94.2	611.4	10801.8	62.7		0.24	5.4	34.8	487.3	3.9
0.26	83.4	484.0	8763.4	68.6		0.26	21.3	139.9	1789.1	15.2
0.23	94.7	695.0	11250.5	54.2		0.26	4.8	31.8	434.8	3.0
0.25	62.8	423.2	7144.6	42.6		0.25	10.4	63.2	849.8	6.1
0.24	109.5	781.8	14016.6	86.0		0.25	6.2	39.3	851.8	6.3
0.25	68.2	405.5	6200.4	34.7		0.25	18.1	114.5	1645.2	10.0
0.24	99.7	608.9	10148.9	50.3		0.25	9.2	68.4	847.7	5.1
0.25	89.1	600.2	10689.5	91.5		0.25	20.7	125.1	1658.3	15.5
Overall										
Uni_D-9						Uni_ND-1				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	89.7	574.7	10557.3	55.6		0.24	25.1	161.0	2481.8	13.9
0.25	99.0	709.3	12228.9	95.3		0.25	23.3	141.0	1871.0	15.8
0.25	94.1	573.8	10454.4	60.7		0.25	5.4	33.3	504.7	4.0
0.25	83.7	510.9	8814.8	69.0		0.25	21.3	141.8	1771.2	15.0
0.25	94.7	669.0	12552.9	60.3		0.25	4.6	31.7	424.3	3.0
0.25	62.8	435.9	6495.5	38.9		0.25	10.4	69.1	911.6	6.4
0.25	109.5	770.4	13467.7	82.7		0.25	6.3	41.1	678.2	5.3
0.25	68.2	405.5	6200.4	34.7		0.25	18.1	114.3	1538.2	9.4
0.25	99.9	597.2	9650.1	47.9		0.25	9.2	66.3	847.1	5.1
0.25	88.9	589.7	10463.9	89.6		0.25	20.7	122.1	2169.4	19.8
0.25	**89.1**	**583.6**	**10088.6**	**63.5**		**0.25**	**14.4**	**92.2**	**1319.8**	**9.8**
0.01	**14.3**	**114.1**	**2413.2**	**20.7**		**0.00**	**8.0**	**49.3**	**737.5**	**5.9**

Flexion										
Uni_ND-3						Uni_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	40.0	247.0	5368.7	28.8		0.23	55.3	369.2	6863.4	36.5
0.25	40.5	236.5	3511.9	28.4		0.26	64.9	372.3	7241.3	57.0
0.26	21.6	130.3	1951.0	12.2		0.26	61.4	355.3	6344.0	37.3
0.25	37.8	233.7	2959.8	24.1		0.25	48.9	308.9	4063.4	32.6
0.25	15.5	97.2	1378.8	7.5		0.25	41.9	263.4	3418.9	17.1
0.25	20.5	129.7	2110.8	13.4		0.26	31.4	194.2	3057.6	18.9
0.26	16.4	113.4	1296.1	9.0		0.26	48.3	278.5	3855.6	24.5
0.25	30.4	178.4	2793.6	16.2		0.25	43.5	253.5	4052.7	23.1
0.25	32.0	199.2	2959.2	15.4		0.26	55.3	326.0	5514.1	27.8
0.25	37.7	223.9	3778.2	33.3		0.25	46.2	285.5	4226.3	37.1
Extension										
Uni_ND-3						Uni_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	40.2	271.1	4211.1	22.8		0.23	55.6	355.6	6290.5	33.6
0.25	40.8	258.4	3913.7	31.5		0.25	65.4	378.3	5814.7	46.1
0.24	21.5	136.7	1925.0	12.1		0.24	61.7	387.8	5567.4	32.8
0.25	37.7	235.8	3844.2	30.9		0.25	49.1	309.8	4773.8	38.0
0.26	15.4	92.2	1469.4	7.9		0.25	42.0	254.6	3691.2	18.4
0.25	20.5	129.6	1714.4	11.1		0.24	31.4	209.0	2330.6	14.7
0.24	16.3	119.7	1495.6	10.2		0.24	48.2	299.5	4591.7	29.0
0.25	30.1	172.3	2581.1	15.1		0.25	42.8	248.8	3814.8	21.8
0.25	31.4	201.7	2594.5	13.6		0.25	54.9	334.1	4869.3	24.7
0.25	37.6	214.5	3306.7	29.3		0.26	46.3	259.4	4336.9	38.0
Overall										
Uni_ND-3						Uni_ND-5				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	40.1	259.0	4789.9	25.8		0.23	55.5	362.4	6577.0	35.0
0.25	40.7	247.4	3712.8	29.9		0.25	65.1	375.3	6528.0	51.5
0.25	21.5	133.5	1938.0	12.1		0.25	61.5	371.6	5955.7	35.1
0.25	37.8	234.8	3402.0	27.5		0.25	49.0	309.3	4418.6	35.3
0.25	15.5	94.7	1424.1	7.7		0.25	41.9	259.0	3555.0	17.8
0.25	20.5	129.7	1912.6	12.3		0.25	31.4	201.6	2694.1	16.8
0.25	16.4	116.5	1395.9	9.6		0.25	48.3	289.0	4223.6	26.7
0.25	30.2	175.4	2687.4	15.6		0.25	43.2	251.1	3933.8	22.4
0.25	31.7	200.4	2776.9	14.5		0.25	55.1	330.0	5191.7	26.2
0.25	37.6	219.2	3542.4	31.3		0.25	46.3	272.4	4281.6	37.5
0.25	**29.2**	**181.1**	**2758.2**	**18.6**		**0.25**	**49.7**	**302.2**	**4735.9**	**30.4**
0.01	**9.9**	**59.4**	**1110.4**	**9.0**		**0.01**	**10.0**	**58.0**	**1294.1**	**10.6**

Flexion										
Uni_ND-7						Uni_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.25	64.6	385.9	7311.5	38.8		0.24	71.3	460.3	8558.5	45.3
0.25	91.4	557.3	9059.7	71.0		0.30	96.4	749.4	17300.5	134.3
0.27	84.2	444.1	9680.3	56.3		0.25	93.4	559.1	9777.5	56.8
0.25	69.6	416.2	6705.4	52.8		0.26	79.5	505.1	7339.8	57.7
0.26	70.1	406.6	8281.3	40.1		0.27	85.4	614.5	8925.3	43.2
0.25	49.7	315.2	4628.8	28.0		0.25	73.5	477.8	6557.2	39.2
0.26	81.7	464.6	7401.9	46.0		0.19	101.9	810.5	14312.2	87.8
0.25	56.5	336.8	4884.8	27.6		0.25	66.3	388.5	6176.4	34.6
0.26	85.5	493.7	8587.2	42.7		0.26	88.8	488.6	8153.9	40.6
0.25	64.9	387.3	5546.4	48.2		0.25	85.1	523.3	7404.9	63.8
Extension										
Uni_ND-7						Uni_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.23	63.9	391.2	6508.8	34.7		0.24	71.1	419.5	8037.6	42.6
0.25	91.5	547.3	8913.5	69.9		0.20	96.6	695.9	15543.3	120.8
0.23	84.1	553.6	7898.8	46.1		0.25	93.4	628.1	10685.8	62.0
0.25	70.0	437.8	6342.6	50.1		0.24	79.5	545.1	8543.5	66.9
0.25	71.3	459.9	5726.2	28.0		0.24	85.5	519.8	10799.1	52.0
0.25	49.6	304.8	4279.3	26.0		0.25	73.5	449.3	6687.2	40.0
0.24	80.7	489.4	7942.9	49.3		0.31	101.9	785.4	14347.5	88.0
0.25	56.2	332.8	5343.7	30.1		0.25	66.8	373.8	6621.9	37.0
0.24	85.5	516.7	8319.2	41.4		0.24	88.6	546.6	9249.5	45.9
0.25	64.5	374.0	6338.7	54.8		0.26	85.0	494.3	8220.6	70.7
Overall										
Uni_ND-7						Uni_ND-9				
Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque		Time	Ang. Disp.	Ang. Vel.	Ang. Acc.	Torque
(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)		(s)	(deg)	(deg/s)	(deg/s^2)	(Nm)
0.24	64.3	388.5	6910.2	36.8		0.24	71.2	439.9	8298.0	43.9
0.25	91.4	552.3	8986.6	70.4		0.25	96.5	722.7	16421.9	127.5
0.25	84.1	498.8	8789.5	51.2		0.25	93.4	593.6	10231.7	59.4
0.25	69.8	427.0	6524.0	51.4		0.25	79.5	525.1	7941.7	62.3
0.25	70.7	433.3	7003.7	34.1		0.25	85.5	567.1	9862.2	47.6
0.25	49.7	310.0	4454.0	27.0		0.25	73.5	463.6	6622.2	39.6
0.25	81.2	477.0	7672.4	47.6		0.25	101.9	797.9	14329.8	87.9
0.25	56.4	334.8	5114.2	28.8		0.25	66.6	381.2	6399.1	35.8
0.25	85.5	505.2	8453.2	42.1		0.25	88.7	517.6	8701.7	43.3
0.25	64.7	380.7	5942.6	51.5		0.25	85.0	508.8	7812.8	67.2
0.25	**71.8**	**430.8**	**6985.0**	**44.1**		**0.25**	**84.2**	**551.7**	**9662.1**	**61.5**
0.00	**13.6**	**78.3**	**1531.2**	**13.1**		**0.00**	**11.5**	**126.9**	**3281.2**	**28.0**